AD-A087 525 BOSTON UNIV MA DEPT OF ASTRONOMY F/G 3/2
CORRELATION OF HIGH LATITUDE CORONAL HOLES WITH SOLAR WIND STRE--ETC(U)
APR 80 K B BAKER, M D PAPAGIANNIS F19628-77-C-0189
UNCLASSIFIED ACBU-SER-II-71 AFGL-TR-80-0123 NL

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AFGL-TR-80-0123

CORRELATION OF HIGH LATITUDE CORONAL HOLES WITH SOLAR WIND STREAMS HIGH ABOVE OR BELOW THE ECLIPTIC

Kile B. Baker
Michael D. Papagiannis

Department of Astronomy
Boston University
725 Commonwealth Avenue
Boston, Massachusetts 02215

Scientific Report No. 3

April, 1980

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-80-0123	2. GOVT ACCESSION NO. AD-A087 525	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Correlation of High Latitude Coronal Holes with Solar Wind Streams High Above or Below the Ecliptic		5. TYPE OF REPORT & PERIOD COVERED Scientific Report No. 3
		6. PERFORMING ORG. REPORT NUMBER A.C.B.U. SerII, No. 71
7. AUTHOR(s) Kile B. Baker, Michael D. Papagiannis		8. CONTRACT OR GRANT NUMBER(s) F19628-77-C-0189
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Astronomy, Boston University, 725 Commonwealth Ave, Boston, MA 02215		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2311G3 BB
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory, Hanscom AFB, Massachusetts 01731, Monitor/Donald Guidice/PHP		12. REPORT DATE April 1980
		13. NUMBER OF PAGES 56
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Coronal Holes; Solar Wind; Interplanetary Scintillation.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Block 20 (Abstract) continued:

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Kile Baker and Michael D. Papagiannis

Dept. of Astronomy, Boston University

Boston, Massachusetts 02215

ABSTRACT

We have correlated the positions of high latitude coronal holes, as determined from the Helium 10830 Å spectroheliograms, with the velocities of solar wind streams high above or below the ecliptic, which could have originated from the same positions as the coronal holes. The solar wind speeds were determined from interplanetary scintillation (IPS) measurements made at the University of California at San Diego and at the Toyokawa Observatory in Japan. The correlation covered the two and a half year period, January 1, 1977 to June 30, 1979, during which there were no large equatorial coronal holes present, since we were approaching solar maximum. We have found that these high latitude coronal holes are often, but not always, correlated to high speed solar wind streams. The lack of a clearer correlation can be attributed to uncertainties in the solar wind velocities obtained from IPS measurements, to uncertainties in the exact boundaries of the coronal holes, and to the deflection or attenuation of relatively weak solar wind streams in interplanetary space.

1. INTRODUCTION

The correlation of large equatorial coronal holes with high speed solar wind streams was established by the Skylab mission (Krieger, Timothy, and Roelof, 1973; Kopp and Orrall, 1977; Hundhausen, 1977). It was reasonable, therefore, to suppose that all coronal holes must produce high speed wind streams, but such a general relationship is quite difficult to demonstrate. In fact, Hundhausen (1977) has suggested that the correlation may not hold true for all coronal holes and that only the large equatorial coronal holes produce high speed solar wind streams. The main problem in testing the extent of this relationship is the difficulty in obtaining solar wind data high above or below the ecliptic. The only method available at present to do so is by estimating the solar wind speeds from the interplanetary scintillation of point radio sources. It is to this method, therefore, that we have turned our attention in this study.

A general correlation of large coronal holes with solar wind velocities determined from interplanetary scintillations was carried out in the 70's at the University of California, San Diego. Rickett, et al. (1976) found that about half of the large coronal hole passages seen over several solar rotations were associated with high speed solar wind streams. A more definitive correlation was performed by Sime and Rickett (1978) in which the IPS data were folded over using a folding period of one Carrington rotation, and were then compared with similarly folded K coronameter data. This convincingly demonstrated the correlation of high speed solar wind streams with large coronal holes that persist for several solar rotations and can be observed by the K coronameter. It did not answer, however, the more general proposition that all coronal holes are associated with high speed solar wind streams.

Recently, Rickett and Coles (1979) have found that as we are approaching solar maximum, the average solar wind velocities at high solar latitudes are lower than what they were near solar minimum. It is quite probable that this result reflects the shrinking of the polar coronal holes near solar maximum, but other possibilities cannot be excluded.

For the past several years, there have been only two groups making regular interplanetary scintillation measurements, namely the University of California, San Diego and the Toyokawa Observatory in Japan. Of these two groups, the UCSD data were more useful for our purposes because they were more consistent and more readily available, since they are published monthly in the Solar Geophysical Data Prompt Reports. The Toyokawa data are presently available only up to June 1978 and as a rule provide less complete coverage. Thus in our two and a half year correlation, for the first year and a half (January 1, 1977 to June 30, 1978) we had data from both UCSD and Toyokawa, but for the last year (July 1, 1978 to June 30, 1979) we had only the UCSD data.

2. IPS MEASUREMENTS

Both groups, UCSD and Toyokawa, measure the interplanetary scintillation by observing strong point radio sources with widely spaced radio telescopes. The UCSD measurements are made at a frequency of 74 MHz using a 3 element system, whereas the Toyokawa measurements are made at 69.3 MHz also with a 3 element system. Details of how the measurements are made can be found in the February supplement to Solar Geophysical Data of each year, as well as in several papers devoted to this subject (Armstrong and Coles, 1972; Coles and Rickett, 1976; Coles and Kaufmann, 1978; Watanabe et al., 1973).

An important concept in the interpretation of the data is the existence of a "scintillation point", P, along the line of sight from the earth to the radio source where the scintillation peaks. Obviously, the scintillation observed at the earth represents an integral of scintillations over the entire path from the earth to the radio source, but along most of the path the contributions are negligible. The "scintillation point" is the point along the path where the contribution to the total scintillation peaks. The actual position of this point depends on the density spectrum of the plasma along the line of sight, but for most reasonable cases the "scintillation point" is the point of closest approach of the line of sight to the sun. If, however, the closest approach to the sun happens to be closer than 0.3 A.U. to the earth, the point P is taken to

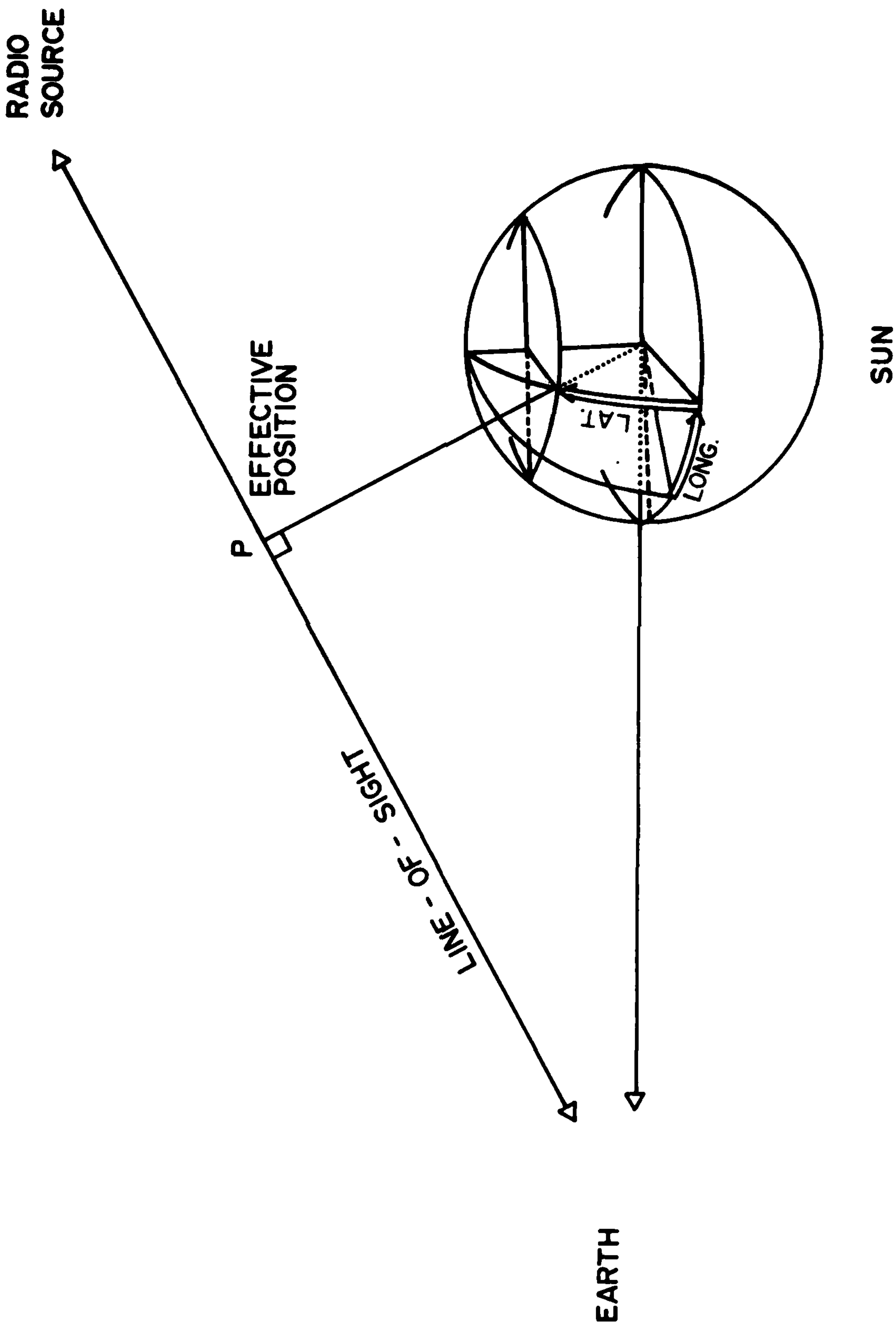
RADIO SOURCE
EFFECTIVE POSITION
P
LAT.
LONG.
SUN
LINE - OF - SIGHT
EARTH

FIGURE 1

be at a distance of 0.3 A.U. from the earth along the line of sight.

As the earth moves around the sun, the position of the point P relative to the sun and the earth keeps changing. Figure 1 shows the geometry of the observations and defines the heliocentric latitude of P and the difference in solar longitude between point P and the earth. These two parameters, along with the distance of the point P from the sun, are tabulated at 10 day intervals for each of the eight radio sources used in the observations and these tables are published together with the scintillation data. The radio sources used for the scintillation measurements are listed in Table 1.

TABLE 1
Scintillation Sources

Source	R.A.	DEC.	UCSD	TOYOKAWA
3C48	0134	+33	yes	yes
3C144	0531	+21	yes	yes
3C147	0538	+50	yes	yes
3C161	0624	-05	yes	no
3C237	1005	+08	yes	no
3C273	1226	+02	yes	no
3C298	1416	+06	yes	yes
3C459	2314	+03	yes	no

Figure 2 shows the change of the heliocentric latitude of P throughout the year for each of the radio sources. Figure 3 shows the change in the difference in heliocentric longitude between the earth and the point P and finally, Figure 4 shows the variation of the distance of the point P from the sun (in A.U.) for each radio source. Since we were interested in high latitude coronal holes, we focused our attention on the IPS data obtained during periods when the

LATITUDE OF P VS TIME

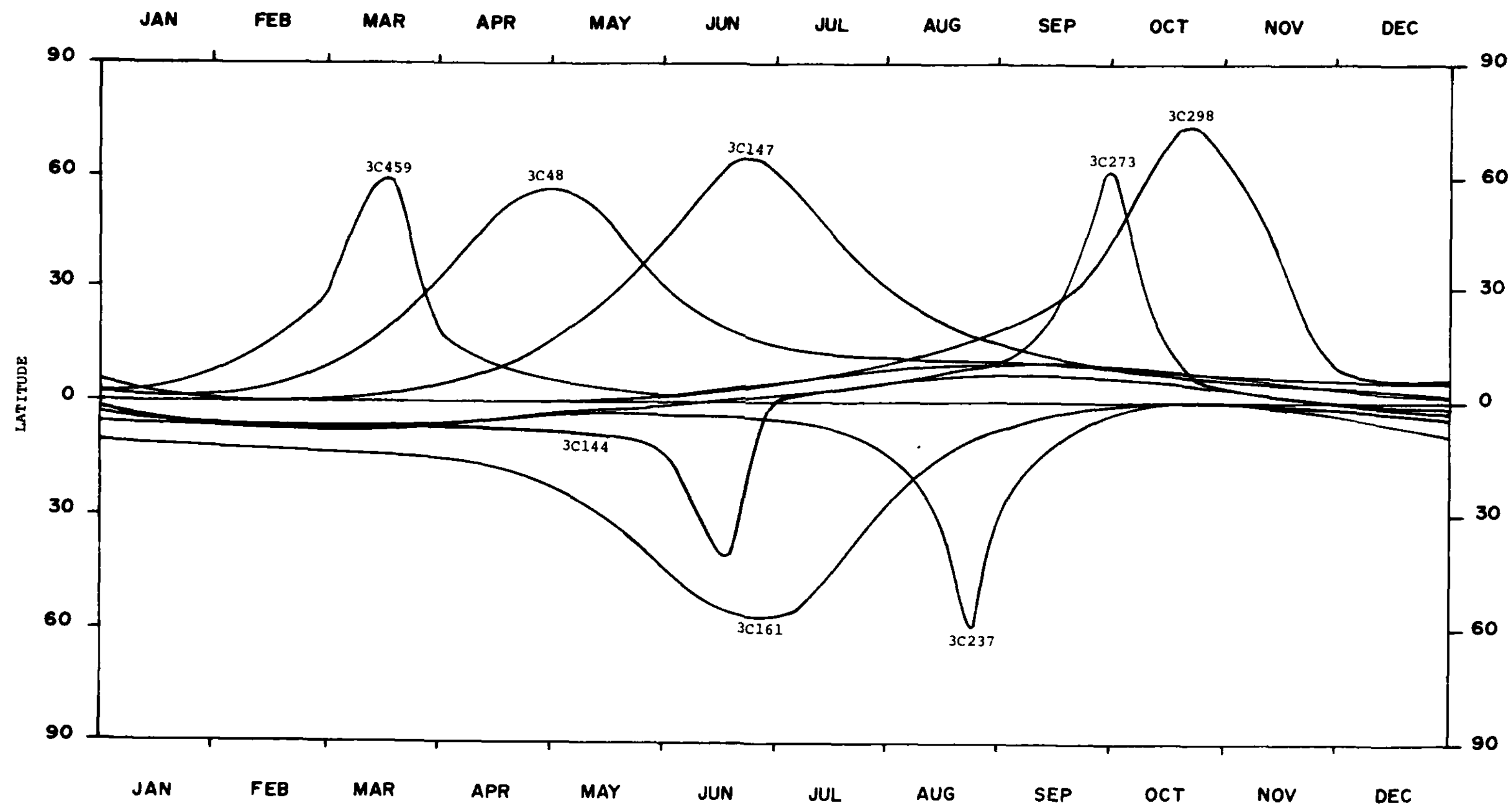

FIGURE 2

LONGITUDE OF P VS. TIME

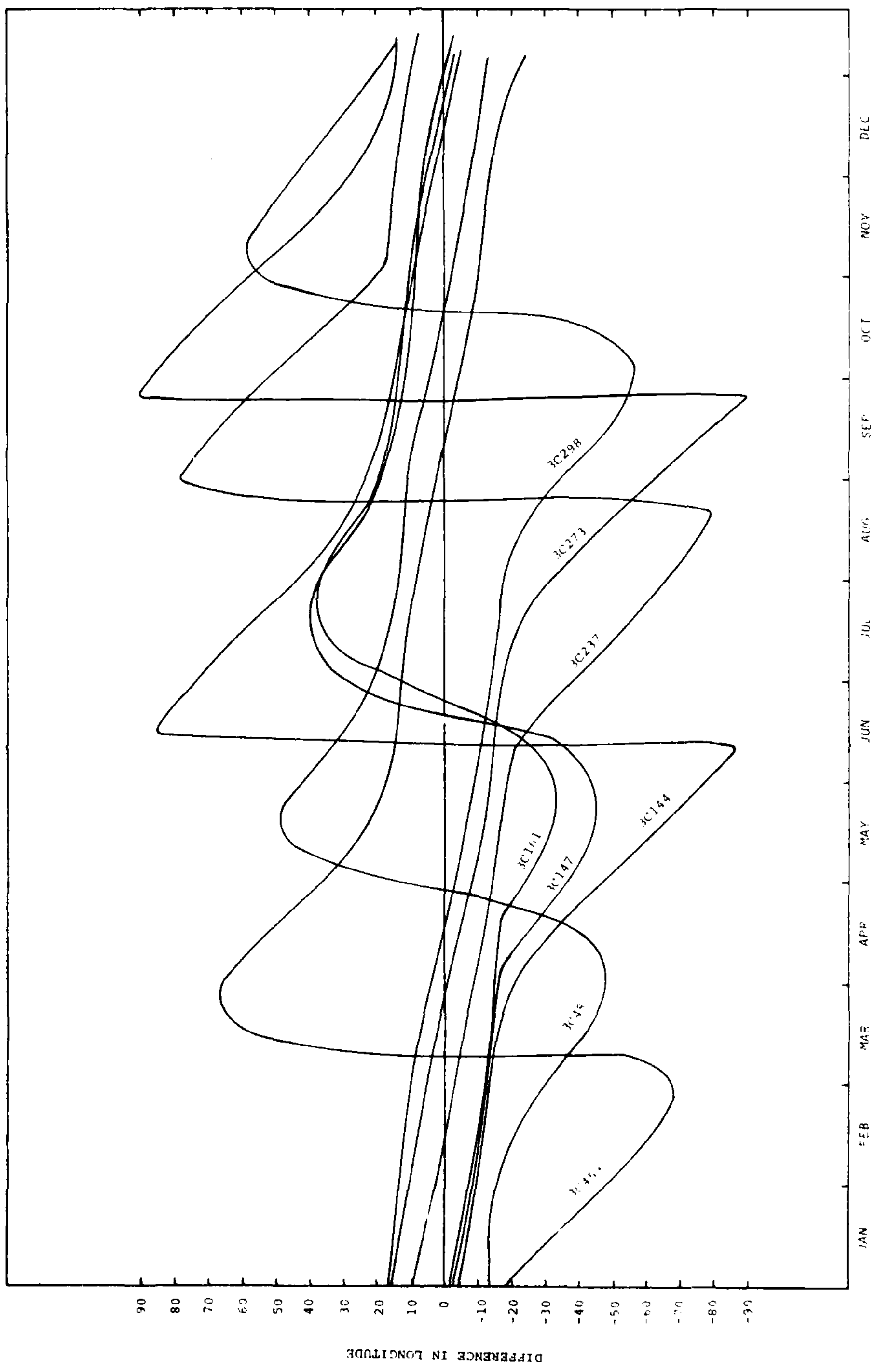

FIGURE 3

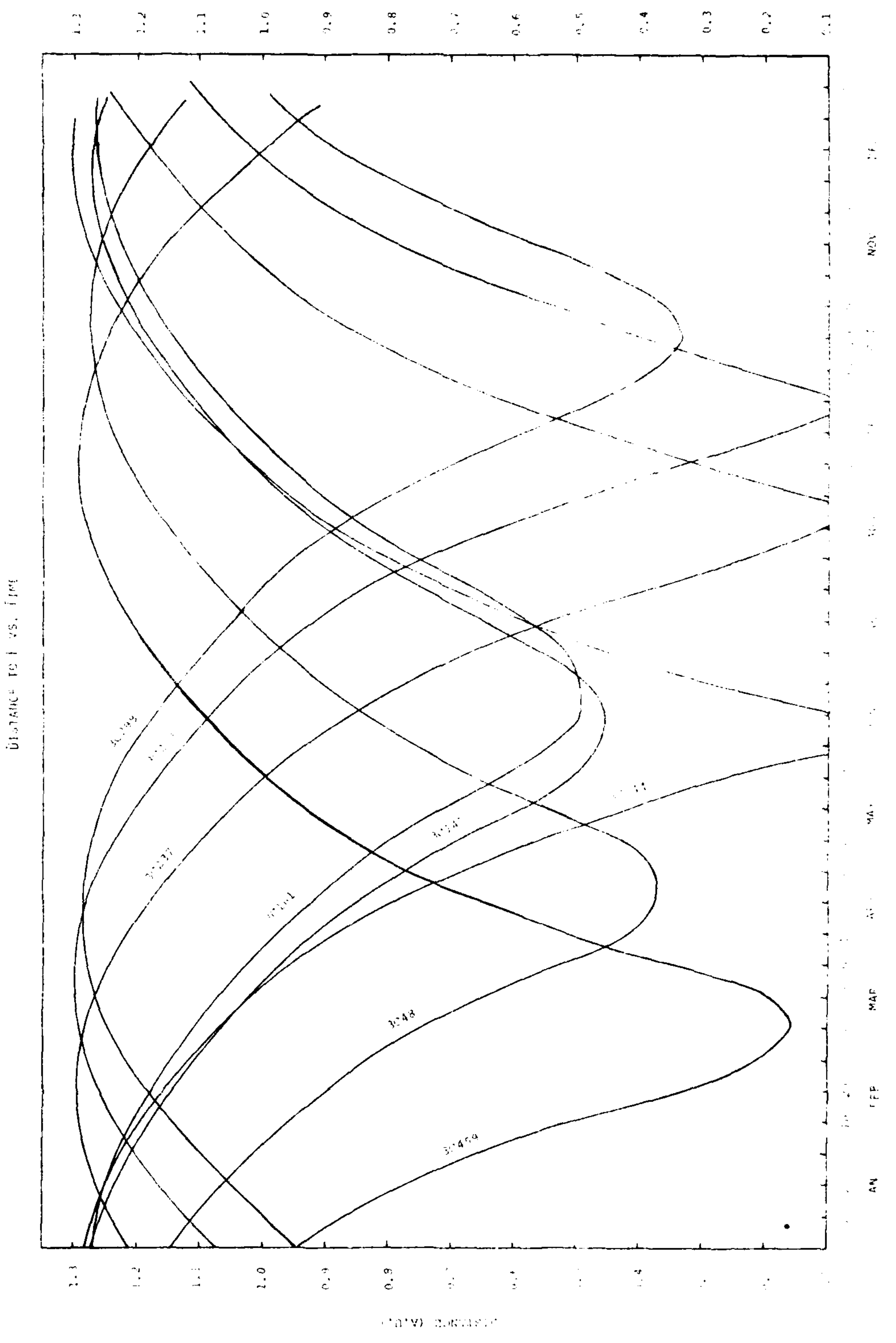

FIGURE 4

IPS Data Availability

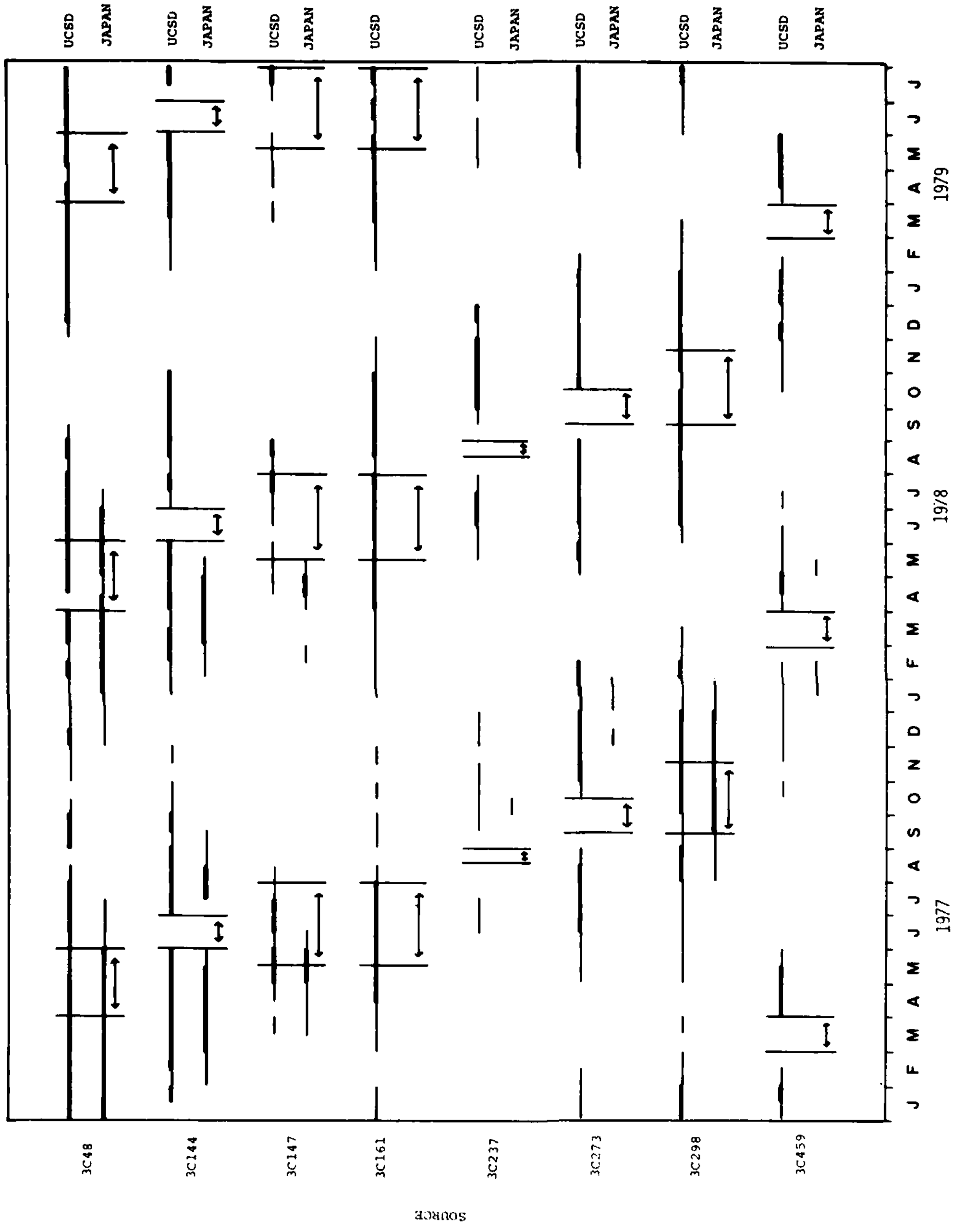

FIGURE 5

point P of a source was at a high solar latitude.

Figure 5 shows the availability of IPS data from each of the 8 radio sources during the two and a half years of our study, with special emphasis on the periods of the year when the solar latitude of the scintillation point, P, was higher than 30 degrees. Thick lines indicate that nearly complete data are available for that period (66% or better). Thin lines indicate partial data (33% or better) are available, while no line indicates that the data available covers less than 33% of the days in that period.

During the two and a half years covered by this study there were a number of high latitude coronal holes for which there were no IPS data available for correlation. The reasons were either that no radio source had a scintillation point that was at a high enough latitude, or that no data were obtained from the high latitude source. The latter is by far the more common cause. When the point P is at high solar latitudes it is also usually quite close to the sun. This makes the observations more difficult and the errors larger, which in turn often leads to a rejection of the data obtained. Despite these problems, there were enough cases during this two and a half year period when both high latitude coronal holes and IPS data were available to allow us to draw some interesting conclusions about their correlation.

3. CORONAL HOLE DATA

In the absence of X-ray data, the most reliable data indicating the presence of coronal holes are the Helium 10830 Å spectroheliograms. Their general validity has been confirmed also in comparisons of Helium 10830 Å coronal holes with radio observations of coronal holes at 11.5 and 21 cm with the Arecibo radiotelescope (Papagiannis and Wefer, 1978). Synoptic maps of coronal holes determined from Helium 10830 Å spectroheliograms have been published monthly by Dr. J. Harvey of the Kitt Peak National Observatory in the <u>Solar Geophysical Data Prompt Reports</u> since January 1977 (Cf. Harvey, et al., 1975).

It should be noted, however, that these synoptic maps of coronal holes are based on observations of the chromosphere, where the He 10830 Å line originates, rather than of the corona, where the X-ray emission originates. Therefore, the actual location and perimeter of a coronal hole in the upper corona might be somewhat different from the location and perimeter determined from the 10830 Å observations. It should be mentioned also that the delineation of a coronal hole boundary from the 10830 Å spectroheliograms is not clear cut and is to some extent subjective.

4. SOLAR RADIO MAPS

There were two periods for which we have additional data on coronal holes from our own radio observations. In early September, 1977 (Papagiannis and Wefer, 1978) there was a coronal hole in the southern hemisphere which shows up very clearly in both the 10830 Å spectroheliograms and the radio observations made at Arecibo (11.5 cm and 21.1 cm wavelengths). Unfortunately, none of the radio sources used in the interplanetary scintillation measurements had a scintillation point, P, at sufficiently high southern latitude to pass through the coronal hole area, and we therefore have no solar wind data to correlate with this coronal hole.

The second period for which we have radio observations was from July 15, 1978 to July 18, 1978. This period was covered not only by our own observations at Haystack and Arecibo, but in addition by numerous other observations from other observatories around the world. During this period, there was a coronal hole in the southern hemisphere which can be seen in the 10830 Å spectroheliograms as well as in the radio maps. The scintillation point, P, for source 3C161 did pass through the latitude range of the coronal hole and thus allowed us to compare the solar wind speed with the position of the coronal hole. This case is discussed in detail below (see Section 7, CASE 4).

5. THE TIME DELAY

In correlating the coronal hole data with the IPS data we have made the following simplifying assumptions:

1. The solar wind streams produce their maximum effect at the scintillation point, P.
2. The high speed solar wind streams travel radially along a straight line from the sun to the scintillation point.
3. The velocity of the solar wind stream remains constant with distance from the sun , maintaining the same value as measured at the scintillation point, P.

With these assumptions, we should expect to see an IPS effect when a coronal hole is properly aligned with the scintillation point. This effect should manifest itself with a delay determined by the time it takes for the solar wind stream to travel from the corona to the scintillation point.

Figures 6 - 17 show the solar wind velocities computed from the IPS data for the different sources together with the synoptic maps of coronal holes. These 10830 Å synoptic maps are based on the latitudinal extent of each coronal hole at the time it crossed the central meridian of the sun. In most cases, however, the coronal hole was aligned with the point P several days before or after the central meridian passage of the coronal hole, and this solar rotation correction must be included in correlating the IPS data with the synoptic maps of the coronal holes. It should be noted here that the shape of the coronal hole may have changed within this few day interval, which introduces some uncertainty in our correlations.

The net delay time, T in days, which may be either positive or negative depending on the longitude difference between the point P and the earth, is given by the expression

$$T = \frac{L}{13.5} + 1724.5\frac{D}{V} \qquad (1)$$

where L is the longitude difference in degrees, D (in A.U.) is the distance from the sun to the point P, and V is the velocity of the solar wind stream in km/sec.

The above formula is slightly ambiguous in actual use because the solar wind speed is not known a priori. In practice, the delay is determined by first determining the rotational delay, and then estimating the wind propagation delay for the approximate dates indicated. The solar wind propagation delay is usually about 1 day and even large errors in the estimated value of V (20 - 30%) make a difference in the total delay of only a few tenths of a day. Because the wind speed makes only a small correction in the total delay, we estimate the average wind speed to the nearest 50 km/sec.

Note that L is changing in time, but usually this change is slow and we can take the value of L at the time the coronal hole crossed the central meridian. However, when the latitude of P is near its maximum value, the value of L changes rapidly. In such cases, we must re-estimate the value L would have had on the day the coronal hole was aligned with point P. Thus, the process of determining the net delay, T, becomes an iterative one.

6. CORRELATION CRITERIA

The data analysis of Figures 6 - 17 is given in Table 2 and is summarized in Figure 19. Determining how good a particular correlation is becomes to a considerable extent a matter of judgement. We have grouped the results in four levels of correlation: Very Good, Good, Fair, and Poor. The criteria used for each of these four levels are listed below.

Very Good: a) Dates of high solar wind speed should correspond to within a day of the expected dates. b) The solar wind speed during this period must have been distinctly higher (25% increase or more) than the average estimated from the adjacent periods. c) If the structure of the coronal hole was such that the scintillation point passed in and out of the coronal hole area more than once, this should be reflected in the IPS data. d) If the coronal hole lasted for several Carrington rotations, high speed solar wind streams should have been observed on each pass of the coronal hole (provided the scintillation point is in range on each pass).

Good: a) The rise to a maximum and the fall to a minimum in solar wind speed must have occurred within 2 days of the expected dates. b) The solar wind speed within the expected period should have been higher than average. c) If the point P passed in and out of the coronal hole area more than once, at least half of these changes should correspond to features in the IPS data.

Fair: a) The solar wind speed must have been higher than average during most of the expected period with a starting and ending tolerance of 2 days. b) A close correspondence of the IPS data to coronal hole features is not required.

Poor: a) The solar wind speed stayed near the average value or even below average during the expected period. b) There is little or no correspondence between the IPS data and any coronal hole features.

TABLE 2A - 1977

CORONAL HOLE Start	Stop	IPS Source	Group	Lat.	Long.	Dist.	Speed	Delay	Corr.	No.
3 - 23	3 - 24	3C48	UCSD	+20	-45	0.6	450	-1.2	F	1
3 - 23	3 - 24	3C48	Japan	+20	-45	0.6	600	-1.8	F	1
3 - 29	3 - 31	3C48	UCSD	+30	-48	0.54	500	-1.9	F	2
3 - 29	3 - 31	3C48	Japan	+30	-48	0.54	650	-2.3	F	2
4 - 3	4 - 4	3C48	UCSD	+34	-48	0.49	450	-1.9	G	3
4 - 3	4 - 4	3C48	Japan	+34	-48	0.49	600	-2.3	G	3
4 - 9	4 - 9	3C48	UCSD	+42	-46	0.43	550	-2.2	F	4
4 - 9	4 - 9	3C48	Japan	+42	-46	0.43	650	-2.4	F	4
4 - 22	5 - 7	3C48	UCSD	+62 +56	-24 +36	0.34 0.40	600 600	-0.8 +3.9	G	5
4 - 22	5 - 7	3C48	Japan	+62 +56	-24 +36	0.34 0.40	650 650	-0.9 +4.1	G	5
5 - 15	5 - 15	3C161	UCSD	-30	-31	0.76	500	+0.2	U	6
5 - 30	5 - 31	3C161	UCSD	-34	-34	0.65	550	-0.6	F	7
6 - 3	6 - 4	3C48	UCSD	+26	+40	0.67	?	?	U	8
6 - 4	6 - 5	3C147	UCSD	+51	-43	0.48	650	-2.1	VG	9
6 - 4	6 - 5	3C147	Japan	+51	-43	0.48	600 1000	-2.3	VG	9
6 - 10	6 - 11	3C161	UCSD	-51	-27	0.46	600	-0.5	U	10
6 - 12	6 - 15	3C147	UCSD	+60	-31	0.46	550	-1.0	U	11
6 - 15	6 - 25	3C147	UCSD	+64	-22 +17	0.45 0.46	550	-0.3 +2.7	G	12

TABLE 2a (cont.)

CORONAL HOLE Start	Stop	IPS Source	Group	Lat.	Long.	Dist.	Speed	Delay	Corr.	No.
6 - 24	6 - 25	3C161	UCSD	-58	- 1	0.48	500	1.6	P	13
7 - 2	7 - 4	3C147	UCSD	+58	+32	0.48	700	3.7		
7 - 12	7 - 14	"	"	+46	+41	0.57	700	4.6		
7 - 18	7 - 20	"	"	+40	+41	0.65	650	4.9		
7 - 24	7 - 26	"	"	+34	+39	0.68	700	4.7	G	14
7 - 7	7 - 10	3C161	UCSD	-48	+31	0.53	650	3.8	F	15
8 - 2	8 - 5	3C161	UCSD	-24	+36	0.72	650	4.7	F	16
9 - 27	9 - 28	3C298	UCSD	+40	-56	0.48	400	-2.3	U	17
9 - 27	9 - 28	3C298	Japan	+40	-56	0.48	450	-2.5	U	17
10-12	10-31	3C298	UCSD	+64 +70	-53 +54	0.37 0.36	550	-3.0 +5.2	G	18
10-12	10-31	3C298	Japan	+64 +70	-53 +54	0.37 0.36	550	-3.0 +5.2	G	18

TABLE 2B - 1978

CORONAL HOLE Start	Stop	IPS Source	Group	Lat.	Long.	Dist.	Speed	Delay	Corr.	No.
4 - 29	5 - 2	3C48	UCSD	+62	+12	0.37	450	2.4	U	19
4 - 29	5 - 2	3C48	Japan	+62	+12	0.37	500	2.2	U	19
5 - 14	5 - 15	3C48	UCSD	+44	+49	0.48	500	5.5	P	20
5 - 14	5 - 15	3C48	Japan	+44	+49	0.48	550	5.3	P	20
5 - 21	5 - 24	3C161	UCSD	-33	-34	0.72	55C	-0.4	G	21
5 - 28	5 - 30	3C147	UCSD	+40	-45	0.51	400	-1.3	U	22

TABLE 2b (cont)

CORONAL HOLE		I P S								
Start	Stop	Source	Group	Lat.	Long.	Dist.	Speed	Delay	Corr.	No.
6 - 15	6 - 16	3C147	UCSD	+62	-22	0.45	450	0.0	U	23
6 - 19	6 - 20	3C161	UCSD	-56	-10	0.50	550	0.8	G	24
6 - 28	7 - 1	3C147	UCSD	+60	+28	0.48	450	4.0	F	25
7 - 18	7 - 19	3C161	UCSD	-38	+37	0.56	400	5.3	P	26
7 - 31	8 - 3	3C147	UCSD	+30	+36	0.75	350	6.5	U	27
8 - 28	8 - 30	3C147	UCSD	+16	+16	0.96	400	5.4	U	28
9 - 25	9 - 29	3C298	UCSD	+39	-54	0.54	650	-2.8	F	29
10-16	10-20	3C298	UCSD	+70	-35	0.34	500	-1.5	P	30
10-27	10-31	3C298	UCSD	+65	+50	0.34	500	5.1	P	31

TABLE 2c - 1979

CORONAL HOLE		I P S								
Start	Stop	Source	Group	Lat.	Long.	Dist.	Speed	Delay	Corr.	No.
5 - 19	5 - 28	3C161	UCSD	-31 -40	-33 -34	0.72 0.65	550	-0.3 -0.6		
6 - 21	6 - 26	"	"	-58	- 9 + 3	0.49	550	0.8 1.8		
7 - 19	7 - 21	"	"	-36	+38	0.57	450	5.2	VG	32
6 - 2	6 - 3	3C161	UCSD	-44	-34	0.64	350	0.5	P	33

TABLE 2d
Comments

1. Scintillation point barely touches coronal hole boundary. No high speed wind observed in UCSD data but there is a peak a day later than expected in the Toyokawa data.

2. Missing data at expected start date for UCSD followed by a peak on expected stop date and descent to low speed solar wind immediately after. Toyokawa shows peak at expected start date followed by descent to low speed solar wind on stop date.

3. UCSD data shows peak at expected start date but speed is not very high. Toyokawa data shows high speed solar wind continuing through the expected period.

4. UCSD shows speed rising to peak on expected start date. Toyokawa data shows strong peak on expected start date.

5. See Special Case 1.

6. Missing data. No evidence for a high speed solar wind stream.

7. Peak in the speed in the center of the expected period.

8. Scintillation point barely touches coronal hole boundary. Missing data on expected start date.

9. UCSD shows strong high speed solar wind stream. Speed rises to peak on expected start date with peak at expected stop date followed by immediate descent to low speeds. Toyokawa data shows very dramatic peak at expected date.

10. Missing data

11. Missing data. No evidence for high speed solar wind stream.

12. Incomplete data. Scintillation point barely touches coronal hole boundary. Several peaks in the solar wind speed during expected period.

13. Generally low speed solar wind. Local minimum occurs during period of expected high speed solar wind.

14. See Special Case 2.

15. Scintillation path does not actually pass through coronal hole area. Strong peak in solar wind speed occurs during expected period.

16. Scintillation point barely touches coronal hole

boundary. Missing data during expected period. Peak two days before expected date.

17. Missing data

18. Missing data at expected start date. UCSD shows extended period of high speed solar wind during expected dates. Toyokawa data is more variable but shows distinctly higher than average speeds during expected period.

19. Missing data

20. Local minimum in solar wind speed during expected period of high speeds.

21. Low speed at expected start date, then a rise to maximum on expected stop date followed by descent to low speeds.

22. Missing data.

23. Missing data.

24. Missing data at expected start date. Peak one day after expected date.

25. See Special Case 3.

26. See Special Case 4.

27. Scintillation point barely touches coronal hole boundary. Missing data.

28. Missing data.

29. See Special Case 5.

30. Low speed solar wind during expected period of high speeds.

31. Generally low speeds, but peak occurs on expected stop date.

32. See Special Case 6.

33. Scintillation point barely touches coronal hole boundary. Generally low speed

CORONAL HOLES AND IPS DATA FOR SOURCE 3C48 FROM MARCH 22, 1977 TO JUNE 4, 1977

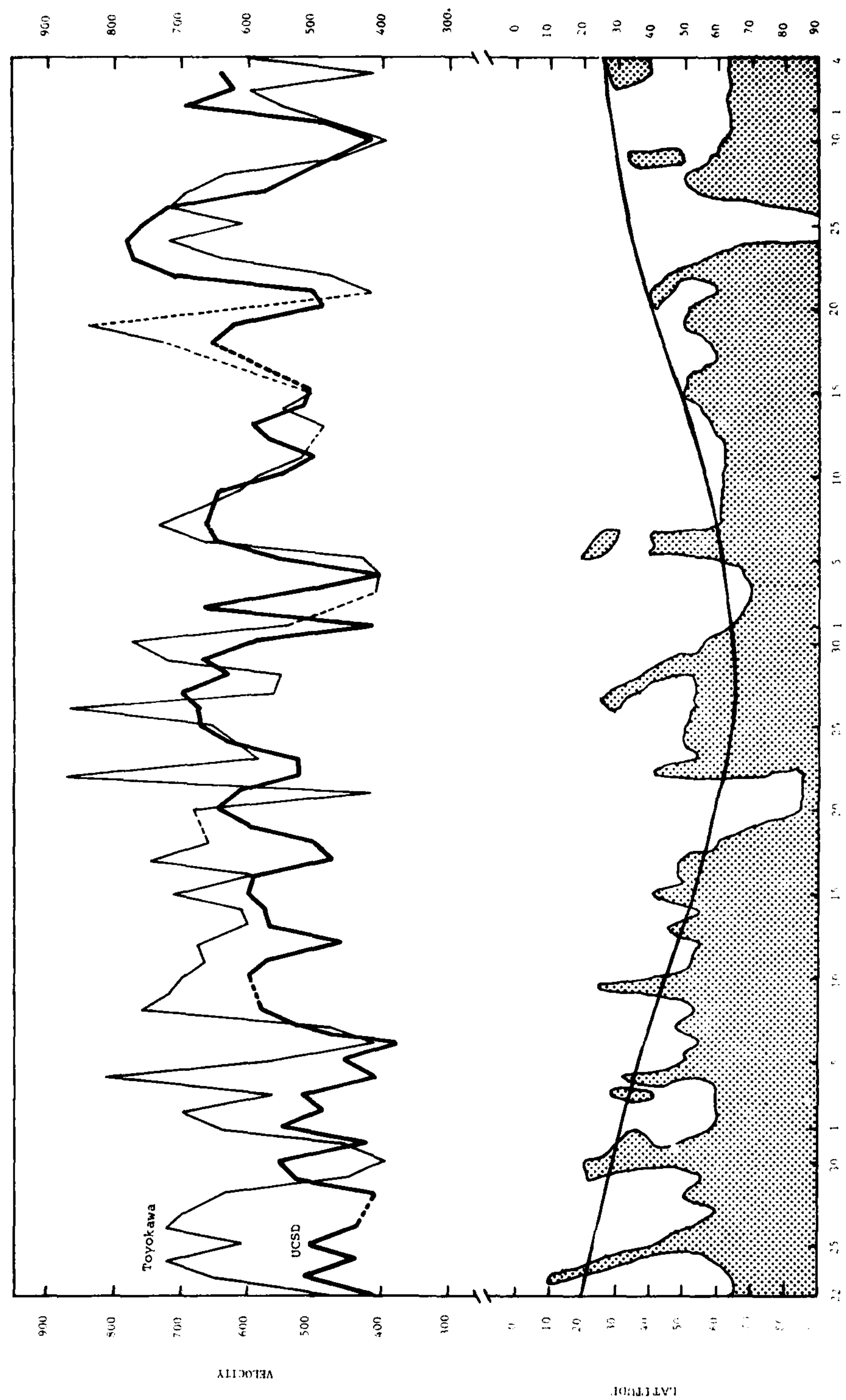

FIGURE 6

CORONAL HOLES AND IPS DATA FOR SOURCE 3C48 FROM APRIL 15, 1977 TO MAY 20, 1977

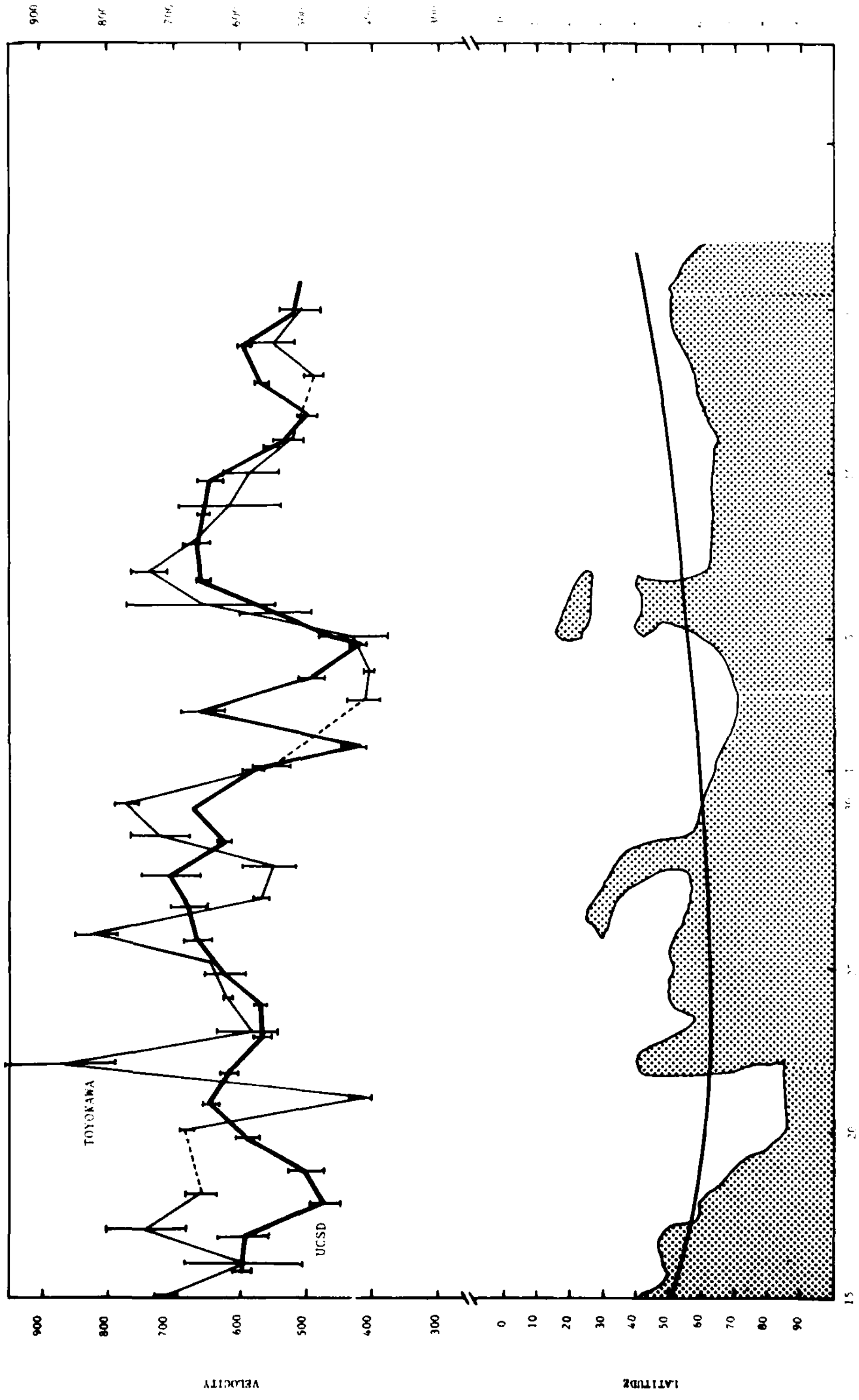

FIGURE 7

CORONAL HOLES AND IPS DATA FOR SOURCE 3C147 FROM MAY 25 1977 TO AUGUST 1977

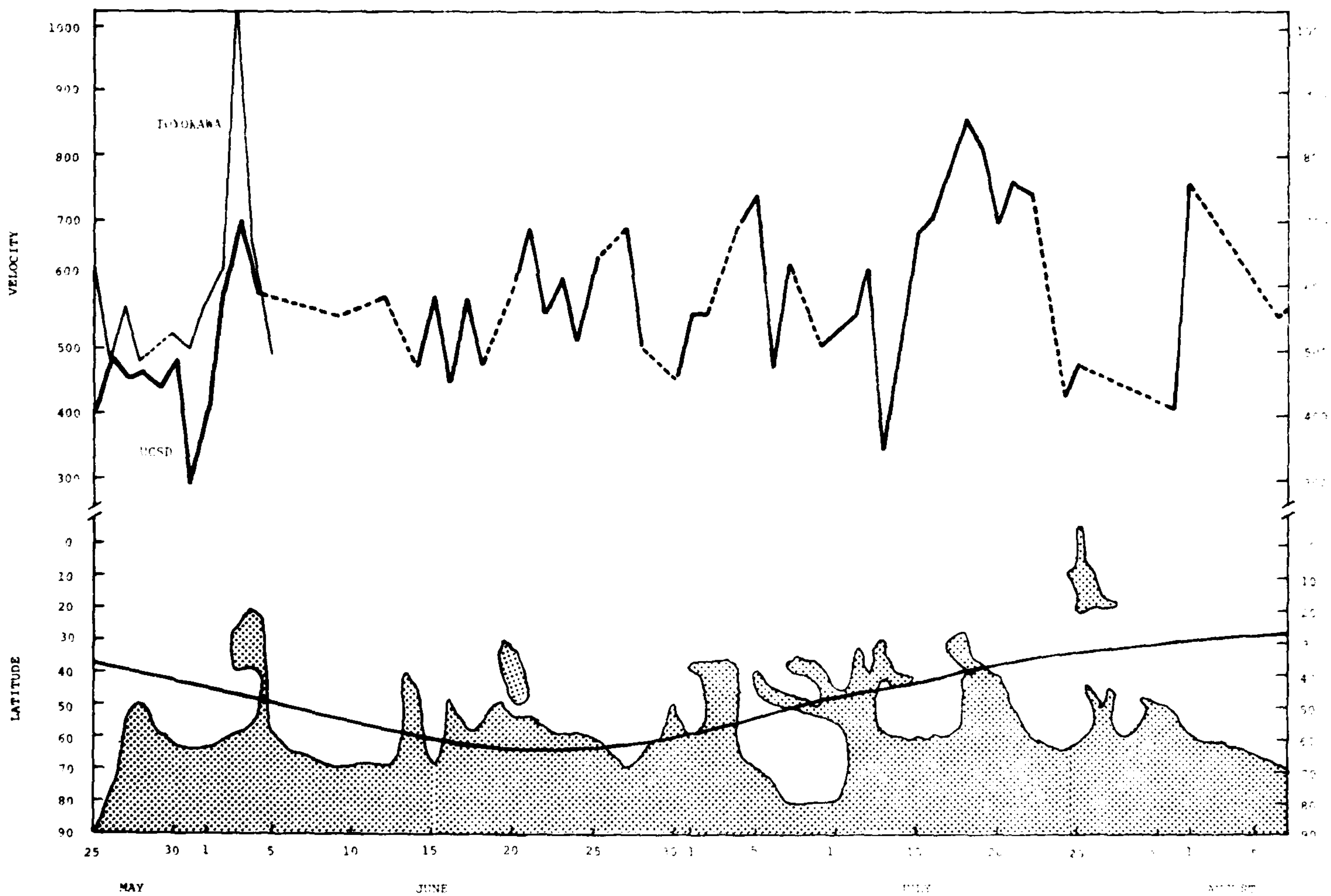

FIGURE 8

Coronal holes and IPS data for source 3C161 from May 1, 1977 to August 12, 1977

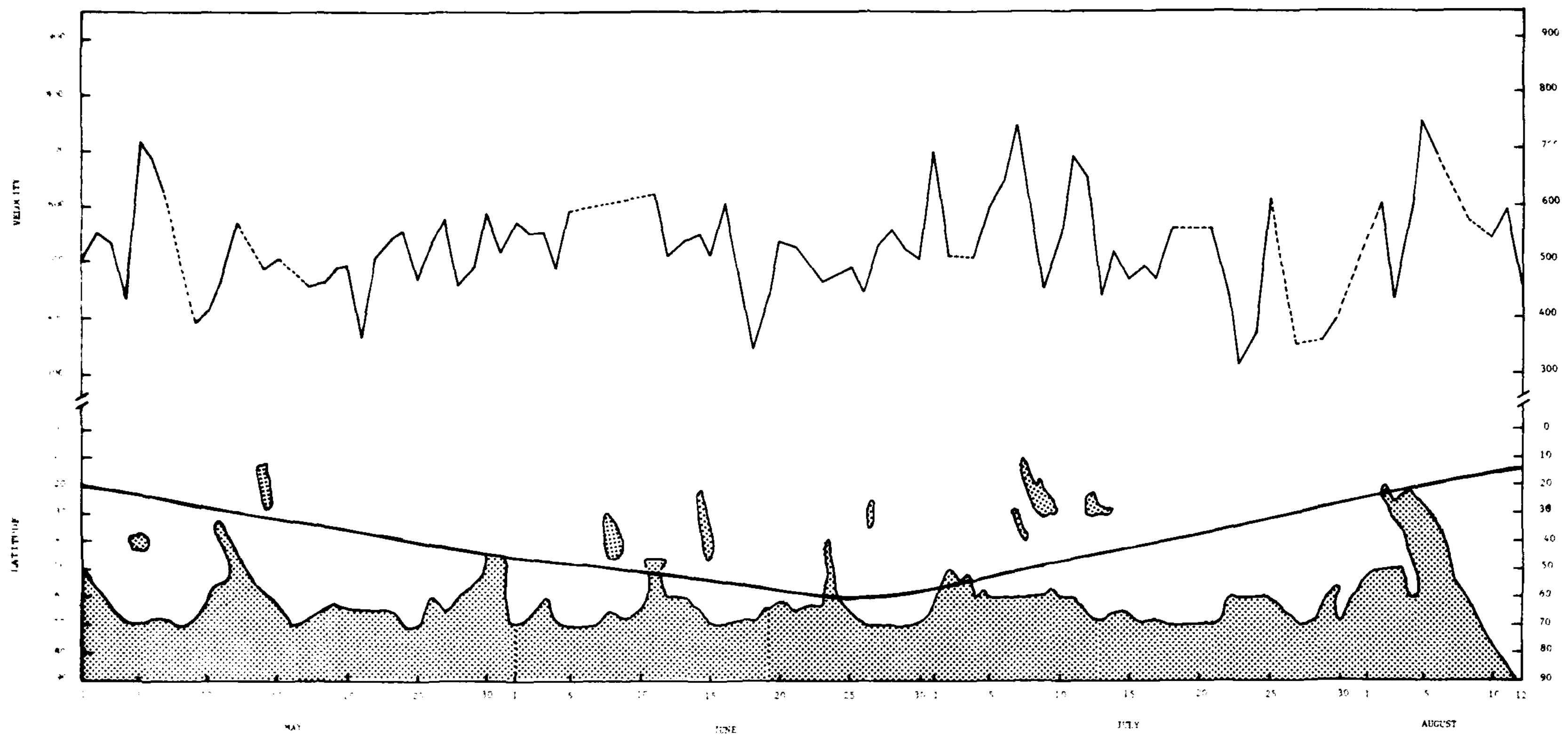

FIGURE 9

Coronal Holes and IPS Data for Source 3C298 from September 20, 1977 to December 3, 1977

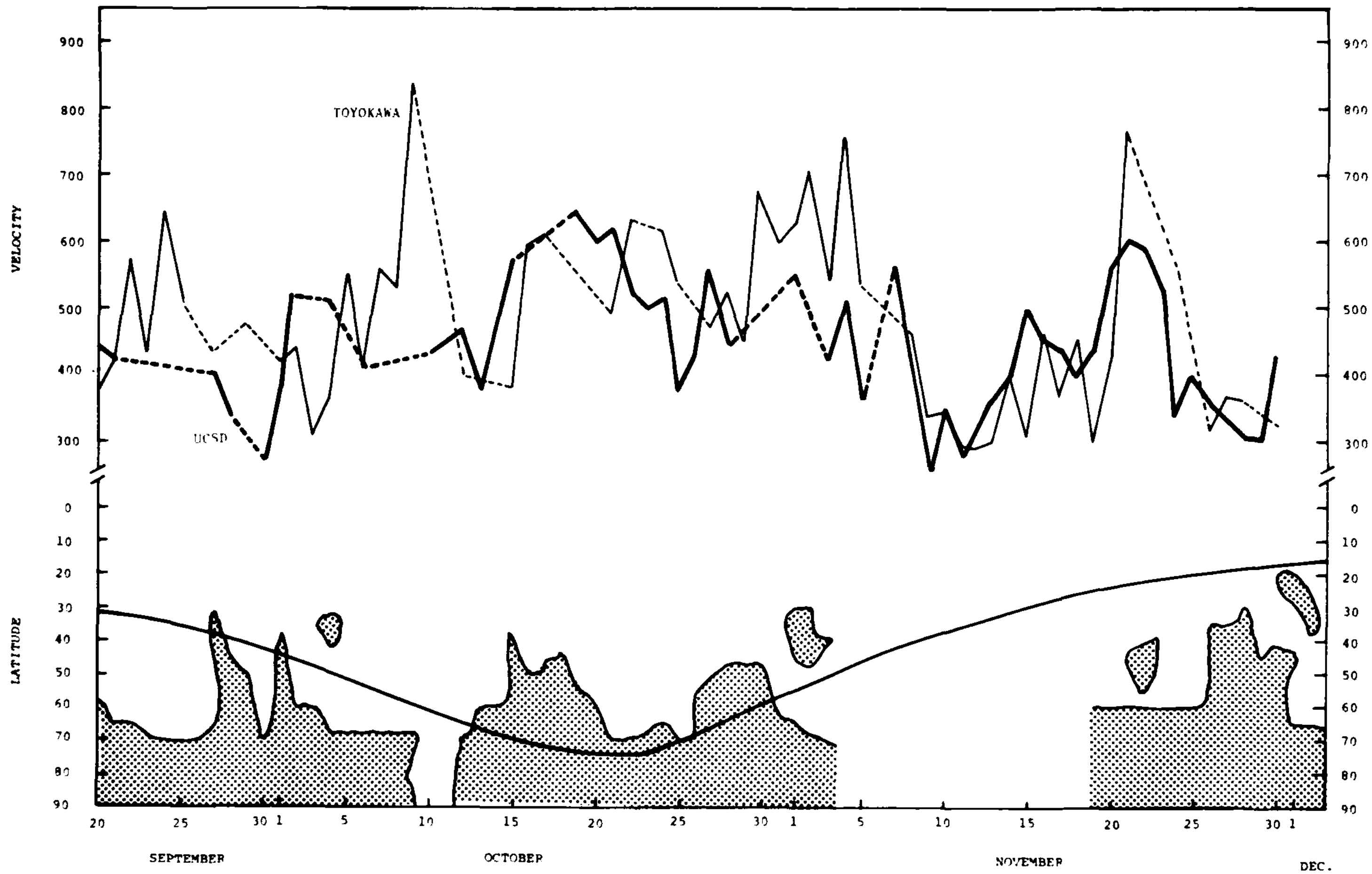

FIGURE 10

CORONAL HOLES AND IPS DATA FOR SOURCE 3C147 FROM APRIL 25, 1973 TO SEPT. 9, 1978

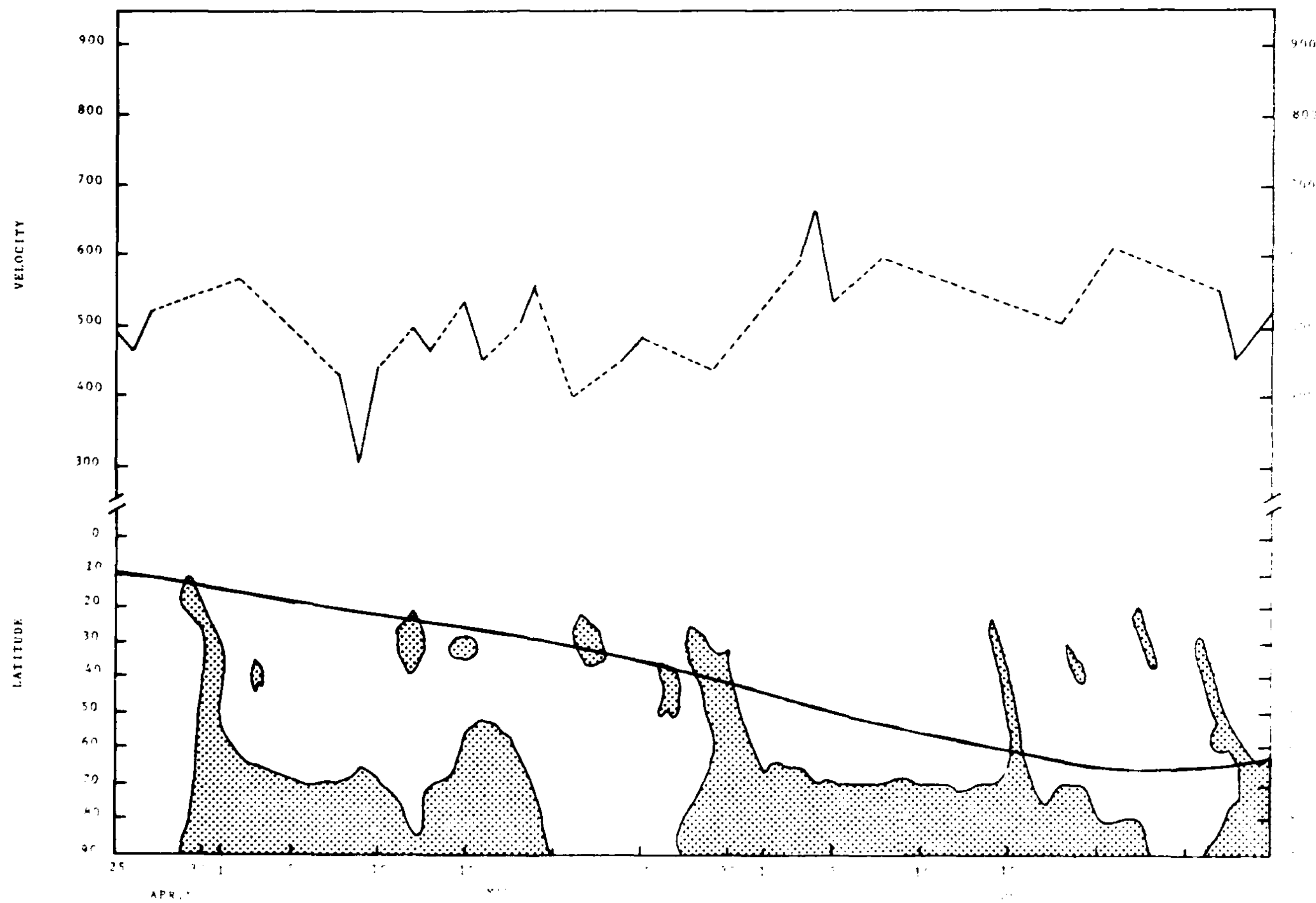

FIGURE 11a

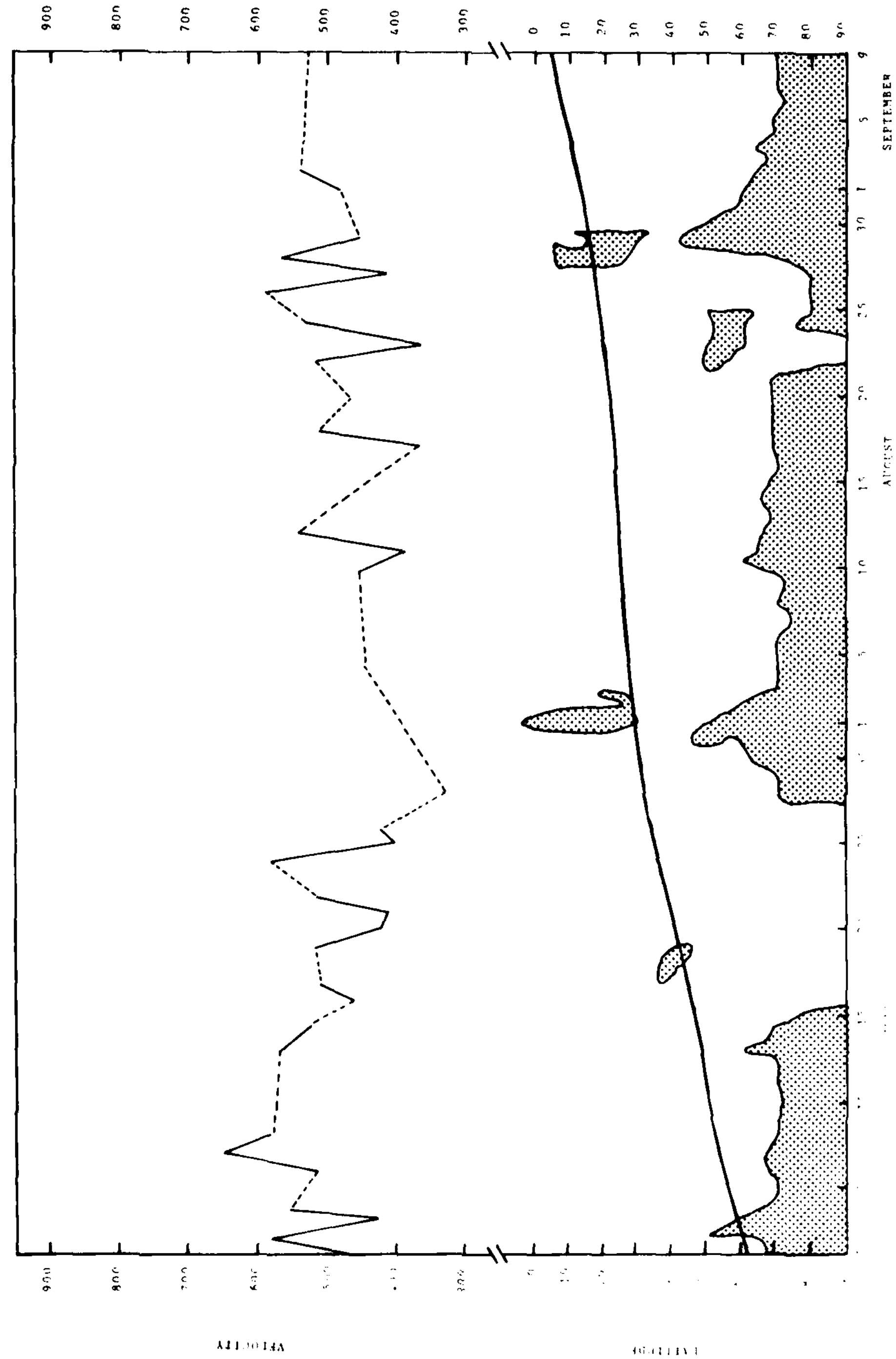
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
SEPTEMBER
AUGUST

FIGURE 11b

Coronal holes and IPS data for source 3C48 from March 25, 1978 to June 7, 1978

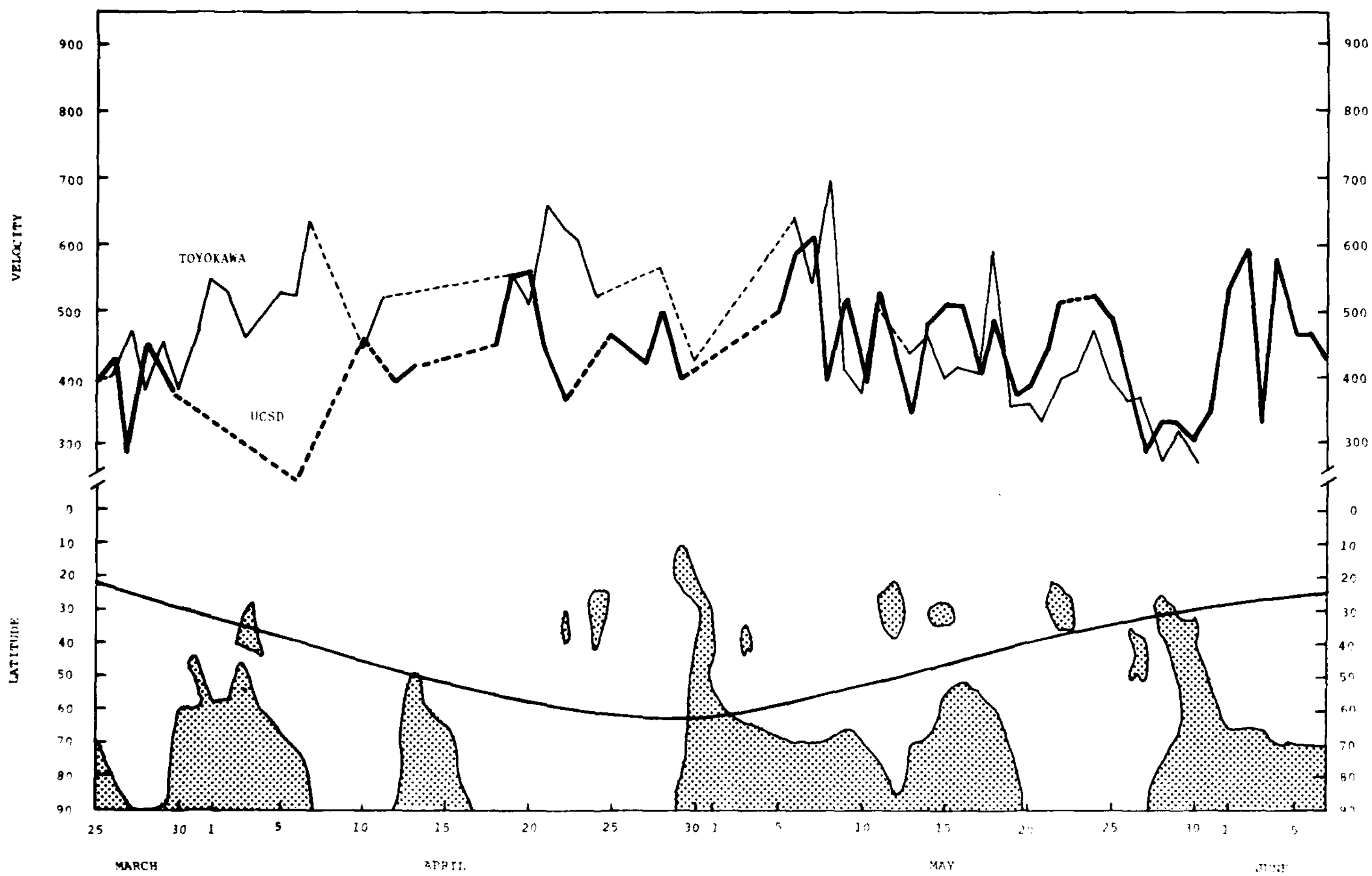

FIGURE 12

[illegible] FROM MAY 17, 1978 TO AUGUST 4, 1978

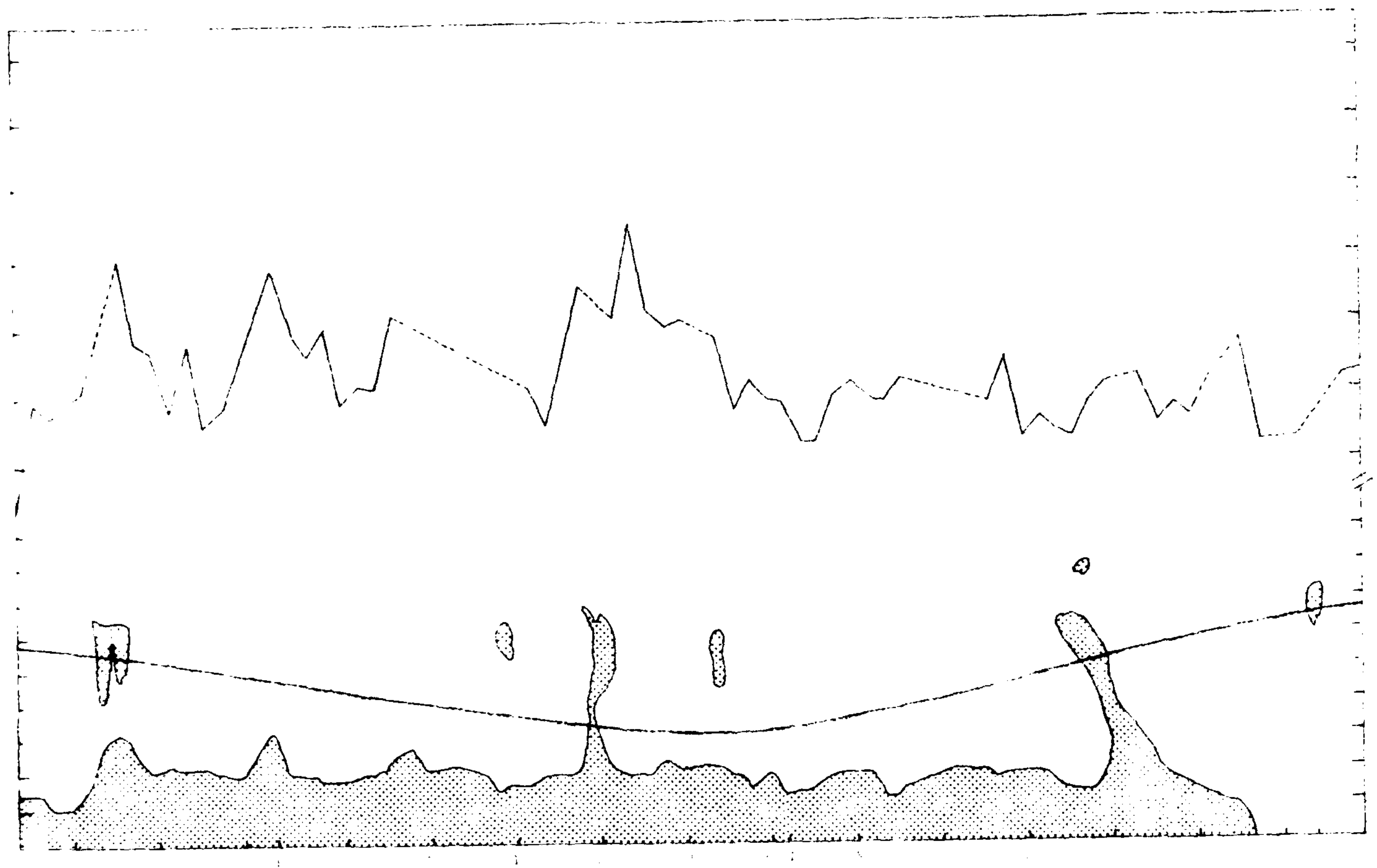

FIGURE 13

Coronal holes and IPS data for source 3C298 from September 15, 1978 to November 28, 1978

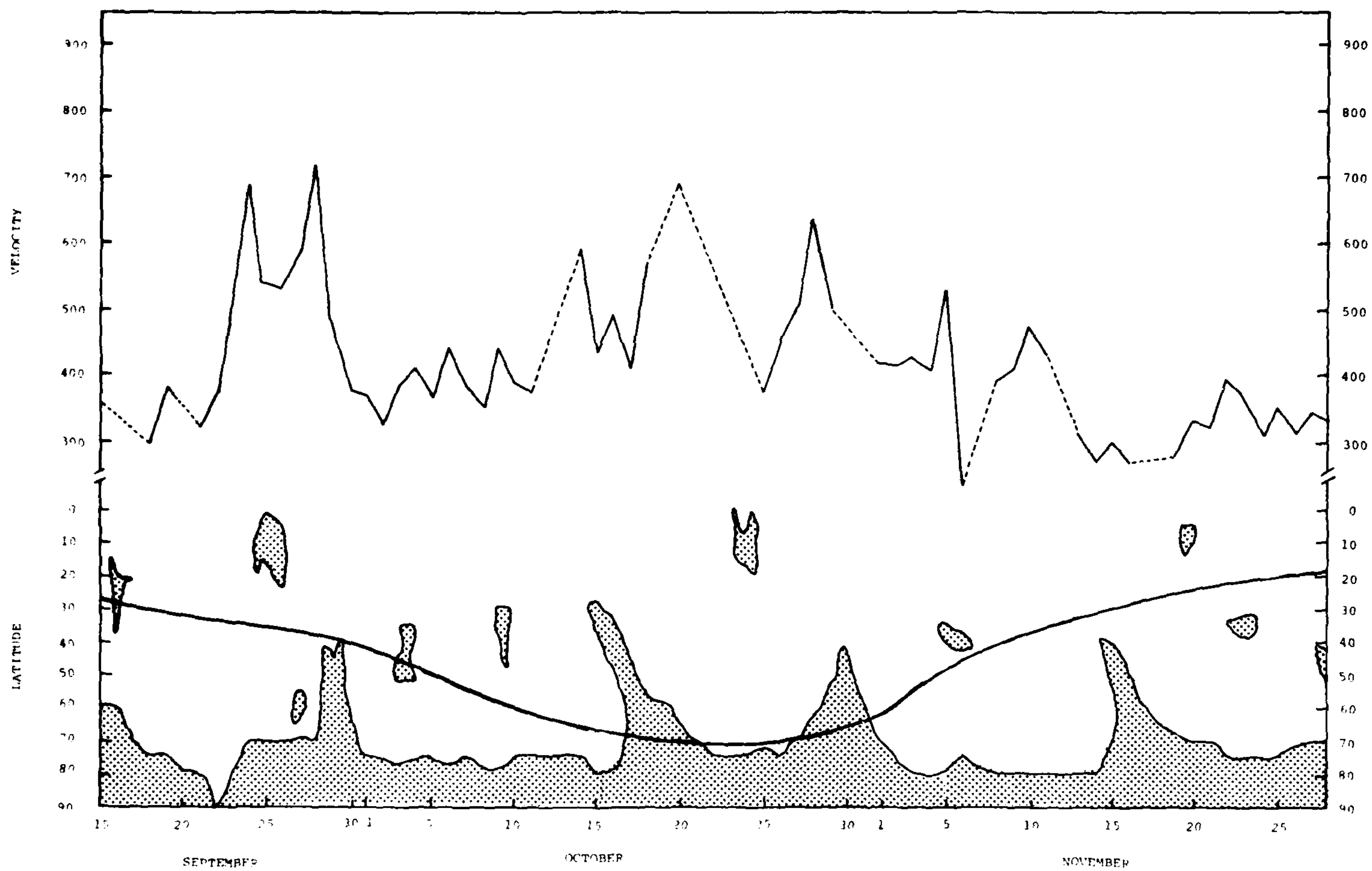

FIGURE 14

CORONAL HOLES AND IPS DATA FOR SOURCE 3C48 FROM MARCH 25, 197[illegible] TO JUNE [illegible], 197[illegible]

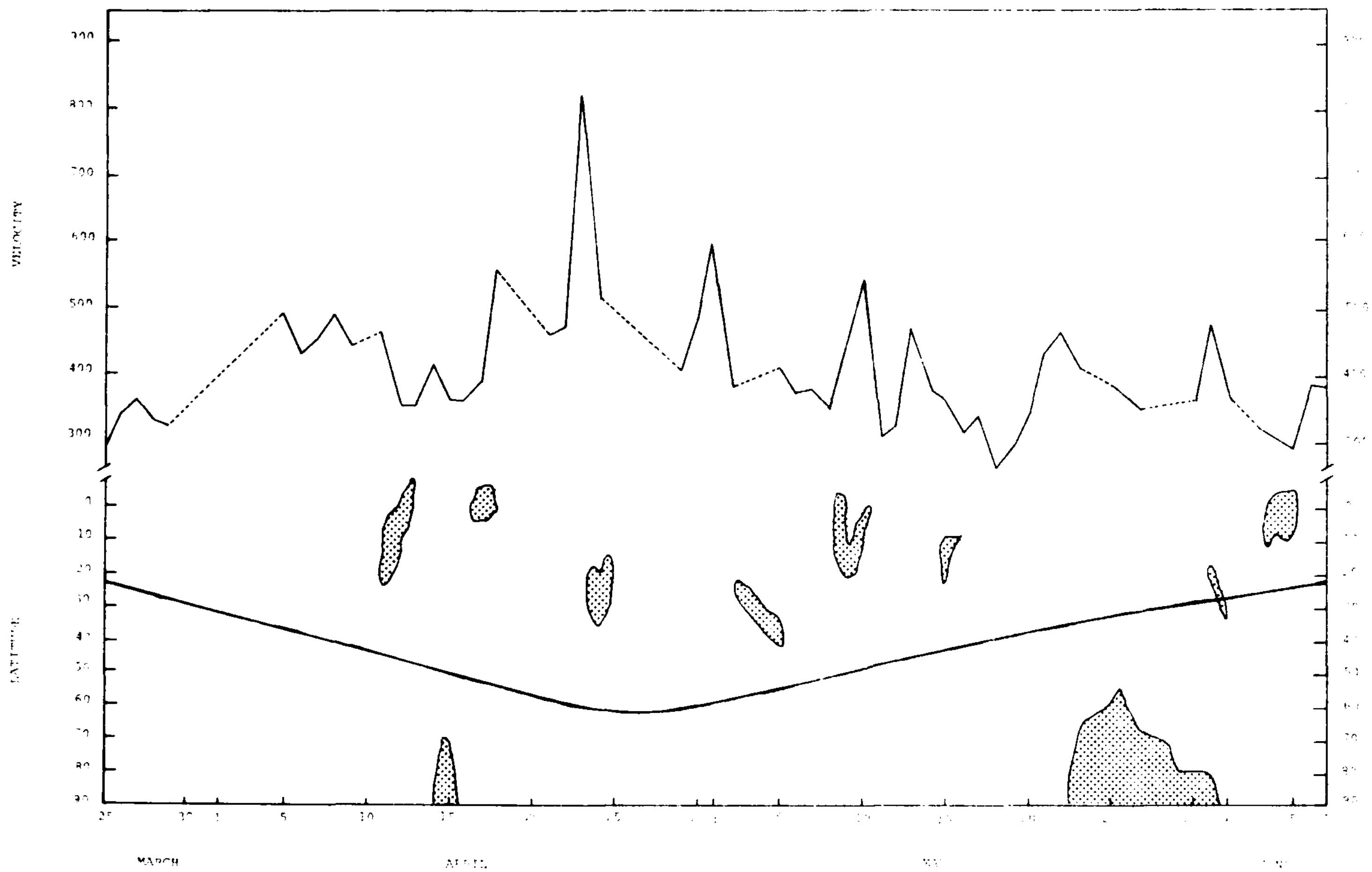

FIGURE 15

... AND IPS DATA FOR SOURCE 3C147 FROM MAY 17, 1979 TO JULY 30, 1979

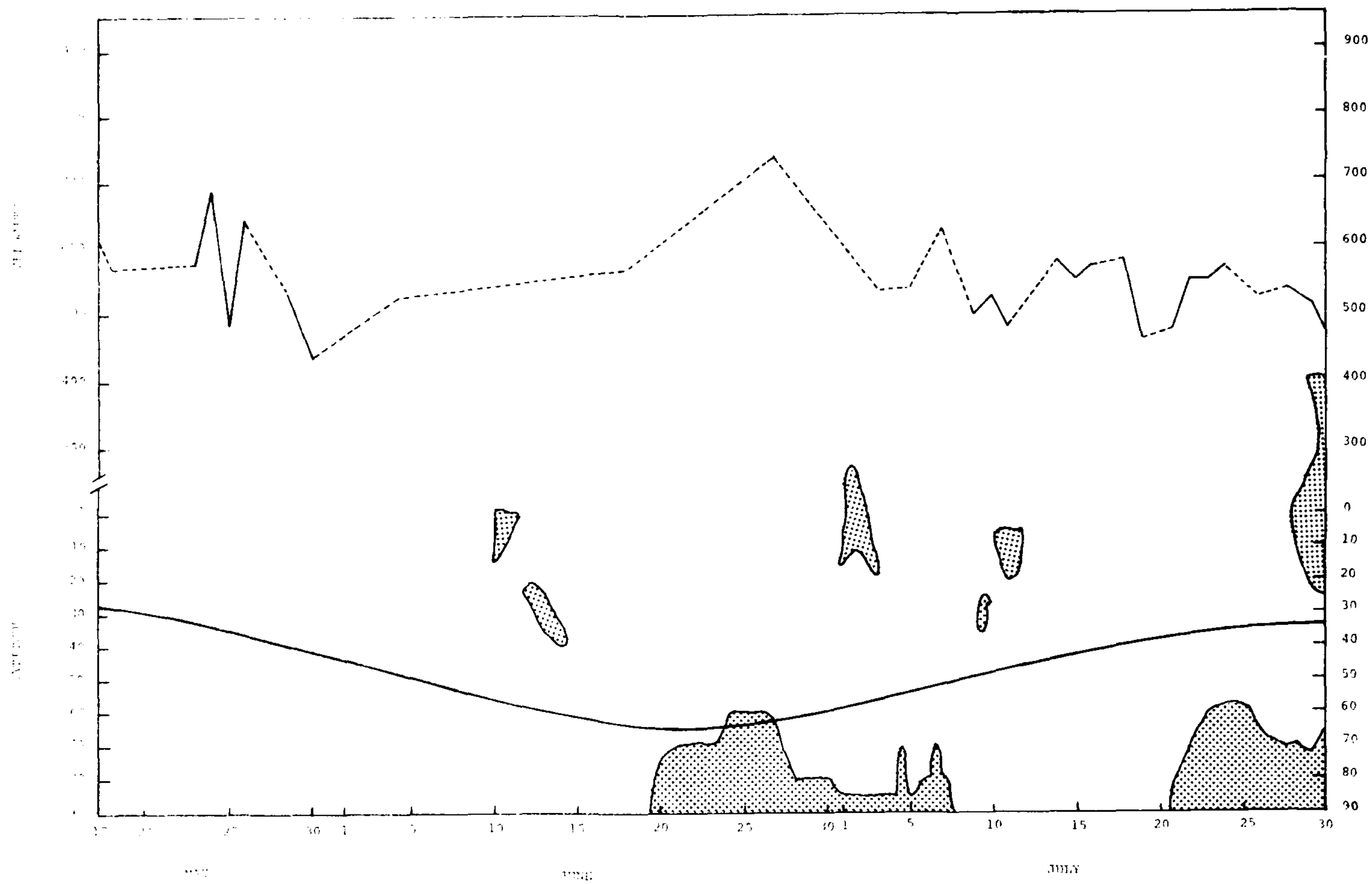

FIGURE 16

Coronal holes and IPS data for source 3C161 from May 17, 1979 to July 30, 1979

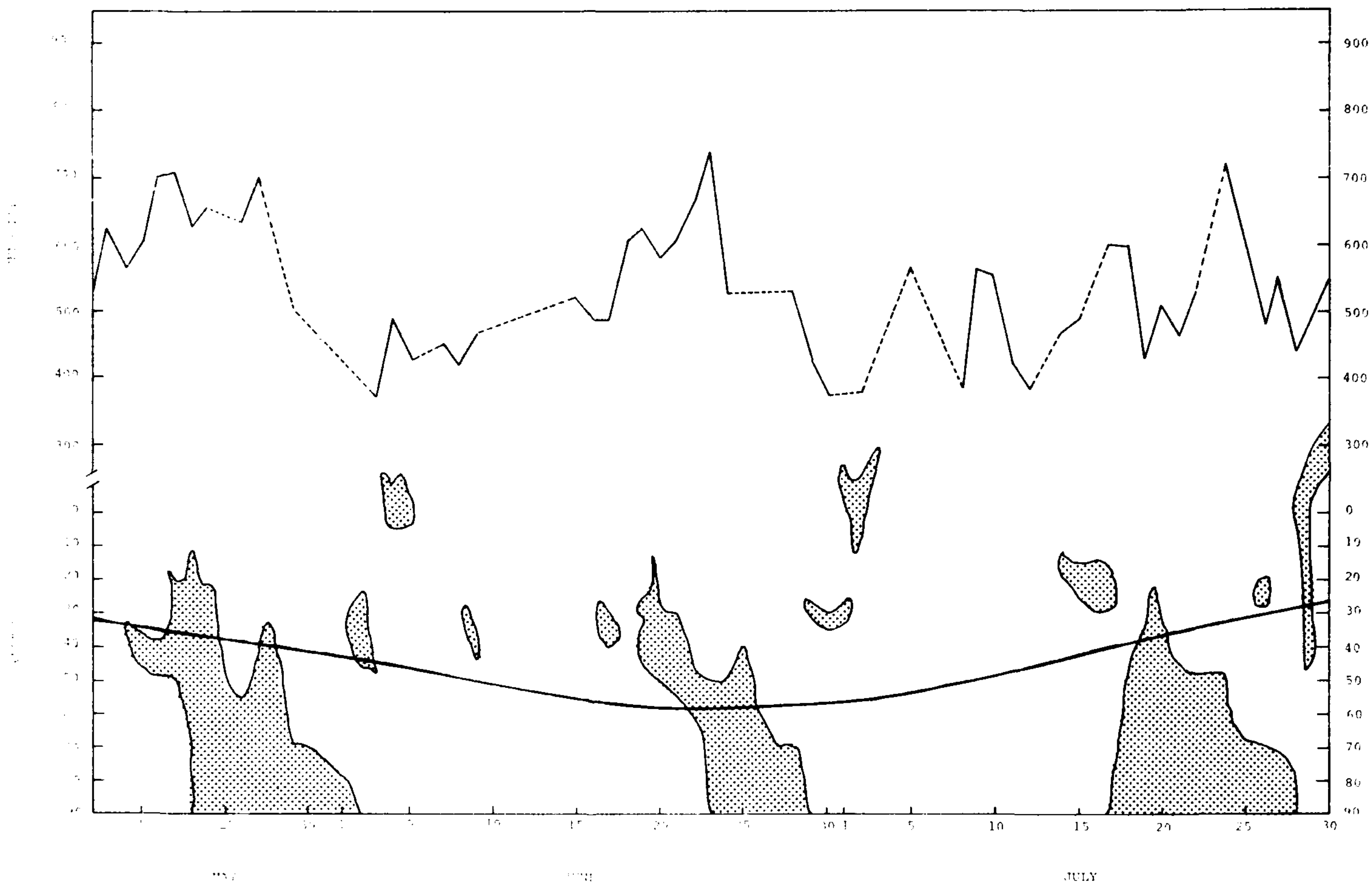

FIGURE 17

7. SPECIAL CASES

In this section we will analyse in some detail six specific cases which represent different levels of correlations between the coronal hole maps and the IPS data. These six cases are marked with an asterisk in Table 2 which lists all the cases. The dates listed at the beginning of each case refer to the synoptic maps and represent the dates at which the coronal hole crossed the central meridian of the sun for the first and last times at the latitude of the scintillation point.

In order to estimate the expected starting and ending dates for the scintillation effects, we must correct for the rotation of the sun to the longitude of the scintillation point and for the time required for the solar wind stream to reach this point (see section 5 above). The necessary modifications for each case are listed in Table 2. Note that in some cases the modification changes dramatically from the beginning to the end of the coronal hole passage. The reason for this is that the longitude of the scintillation point changes rapidly near the peak latitude as the line of sight to the radio source passes directly above or below the sun.

<u>CASE 1, April 22 - May 7, 1977, (Figures 6 & 7)</u>

In late April and early May, 1977 there was a large southward extension of the northern polar coronal hole around Carrington longitude 260. At the same time the scintillation point for the source 3C48 was near its maximum latitude (~63° N), and therefore, the scintillation level of this source should have been affected for an extended period by this coronal hole.

As an example of the method of analysis we have used, we will look at this case in especial detail. In Figure 7 we have expanded the time scale of Figure 6 and have plotted the IPS data from both UCSD and Toyokawa in terms of the universal time (UT) at which each measurement was made.

As can be seen in Figure 7, the boundary of the coronal hole at 63° N latitude reached the central meridian of the sun on or slightly before April 22. The difference in longitude between P and the earth was about -28 degrees on this date. The coronal hole was therefore aligned with the point P approximately two days earlier. On April 20, the difference in longitude was about -30 degrees, so the more correct value for the rotation correction is -2.2 days. This is clearly a situation in which the change in longitude was not very important.

The average solar wind speed (according to the UCSD data) around April 20 was about 600 km/sec, and the approximate distance from the sun to P was about 0.37 A.U. The delay due to the propagation of the solar wind from the sun to P was therefore about 1 day and the net delay (combining the rotational correction with the propagation delay) was about -1 day. We would therefore expect to see a high speed solar wind stream begin on or about April 21.

The UCSD data show a peak in the solar wind speed at this time, but the increase to this peak began about 2 days earlier (April 19). The Toyokawa data, on the other hand, indicate an average solar wind speed of only about 500 km/sec for this period. If, however, the strong peak in the Toyokawa data on April 22 is indicative of the true speed of the solar wind coming from the coronal hole, then the average solar wind speed would be around 700 km/sec. This difference in the estimated solar wind speed makes a difference of only 0.3 day in the delay time, so the expected start date for a high speed solar wind is still around April 21, 1977. The Toyokawa data show a minimum in the solar wind speed on this date, followed by a dramatic increase to nearly 900 km/sec the next day.

Both the Toyokawa and the UCSD data show a local minimum in the solar wind speed around April 23 and 24. Nevertheless, this minimum was in fact distinctly higher than the normal slow speed solar wind and still qualified as part of a high speed solar wind stream. There was no obvious feature in the coronal hole that would account for a decrease in the solar wind speed on these dates, although the latitude of the scintillation point was close to the coronal hole boundary. The UCSD data show a fairly steady high speed solar wind continued from April 24 to May 1. The Toyokawa data, on the other hand, show another local minimum around April 27-28.

The trailing boundary of the coronal hole passed by the central meridian at the latitude of the point P around April 30. The difference in longitude at this time was +10 degrees. Thus, the rotational correction was about +1 day.

Consequently we must check the difference in longitude and the average solar wind speed about 2 days later, May 2 (1 day for rotation and 1 day for the wind propagation). On May 2 the longitude difference was about +16 degrees and the solar wind speed was about 600 km/sec according to the UCSD data and about 450 km/sec according to the Toyokawa data. The distance from the sun to point P on May 2 was about 0.37 A.U. and hence the net delay was +2.2 days for UCSD and +2.5 days for Toyokawa (see equation (1)). In either case, the correct delay was about 2 days and the end of the high speed solar wind stream would be expected around May 2 (as initially estimated). The UCSD data show a very high speed solar wind on this date, and the speed was increasing. However, a day later the solar wind speed again decreased rapidly. It is unfortunate that the Toyokawa data for May 2 is missing, but on May 3 the solar wind speed was quite low and remained low for two days.

The coronal hole boundary and the scintillation point latitude again intersected shortly after May 5. The longitude difference on May 5 was +33 degrees which would indicate a rotation correction of about 2.4 days. Applying the usual 1 day solar wind propagation delay gives a net delay of about 3-4 days. We therefore check the longitude difference and solar wind speed around May 8. The longitude difference on this date was about +40 degrees and the solar wind speed was about 650 km/sec for both the UCSD data and the Toyokawa data. The distance from the sun to P was about 0.42 A.U. and hence the net delay (equation (1)) was about

+4.1 days. The expected date for an increase in solar wind speed is therefore May 9 and not May 8 as originally estimated. Actually, both the UCSD and the Toyokawa data show an increase to high solar wind speeds about 3 days earlier. The solar wind speed would be expected to decrease around May 11, when the point P again moves out of the coronal hole area, and this was in fact observed.

The overall correlation in this case is quite good. The high speed solar wind from May 6 to May 10 started earlier than expected but ended at the right time. The extended minimum in the Toyokawa data from May 3 to May 5 fits well with the period when the latitude of P was outside the coronal hole region, and the extended high speed wind in the earlier period (April 22 - May 1) fits well with the first period during which the point P was within the range of the coronal hole. The most anomolous feature in the IPS data is the peak in the UCSD data about May 3, which does not correlate with any coronal hole feature and is completely at odds with the Toyokawa data.

On the whole the IPS data were well correlated to the coronal hole structure and we consider this case to be a "Good" correlation.

CASE 2, July 2 - July 20, 1977, (Figure 8)

During the entire period from early May to August, 1977 a large polar coronal hole was present in the northern hemisphere with several large extensions. It is unfortunate that the scintillation data for this period [source 3C147] are incomplete. The scintillation data available are also more variable than in the previous case. The peak on July 5, 1977 slightly preceeded the expected date for a high speed solar wind stream, but since the latitude of the scintillation point was very close to the coronal hole boundary for earlier periods, this may represent an example of a certain degree of uncertainty in determining the coronal hole boundaries from chromospheric 10830 Å spectroheliograms.

The solar wind minimum on July 6, 1977 did not correspond to any clear feature of the coronal hole, but the minimum on July 13 did correspond to the period around July 10 when the latitude of the scintillation point was outside the coronal hole area. During the period July 12 to July 20, 1977 the coronal hole boundaries were not clear, which makes the interpretation of the IPS data uncertain. The extended period of high solar wind speeds, however, from July 16 to July 22 corresponded well to the starting and ending dates expected from the extent of the coronal hole, although there was no sign of a decrease in solar wind speeds during the period July 14 to July 17 when the point P was apparently outside the area of the coronal hole.

Overall the IPS data were well correlated to the coronal hole features and we consider this case to be another "Good" correlation.

CASE 3, June 28 - July 1, 1978, (Figures 11a & 11b)

This was another example of a situation in which the latitude of the scintillation point [source 3C147] was just barely within the area of the coronal hole for a period of several days. The initial overlap in their respective latitudes occured on June 28. Four days later there was a peak in the solar wind speed, though not as large as in some other cases, which corresponds well to the delay expected from the solar rotation and the wind propagation time.

This maximum was followed by a minimum one day later and then another rise to a maximum. Missing IPS data makes it impossible to determine the exact date of this second maximum, but it must have been either July 4 or July 5. Another maximum occured on July 7, 1978. This pattern of rapid changes in solar wind speed may be characteristic of situations in which the latitude of the scintillation point skirts the lower boundaries of a high latitude coronal hole.

Because of the multiple peaks in the IPS data which did not correspond to observed coronal hole features, we consider this to be only a "Fair" correlation.

CASE 4, July 18 - July 20, 1978, (Figure 13)

During the period July 15 - July 18, 1978 we recorded the presence of a southern polar coronal hole at several radio wavelengths. Our observations were made at the Haystack Observatory at 0.69, 1.38, 1.93, and 3.81 cm. and at the Arecibo observatory at 11.5 and 21.1 cm. (see Figure 18). This coronal hole was also seen in the 10830 Å

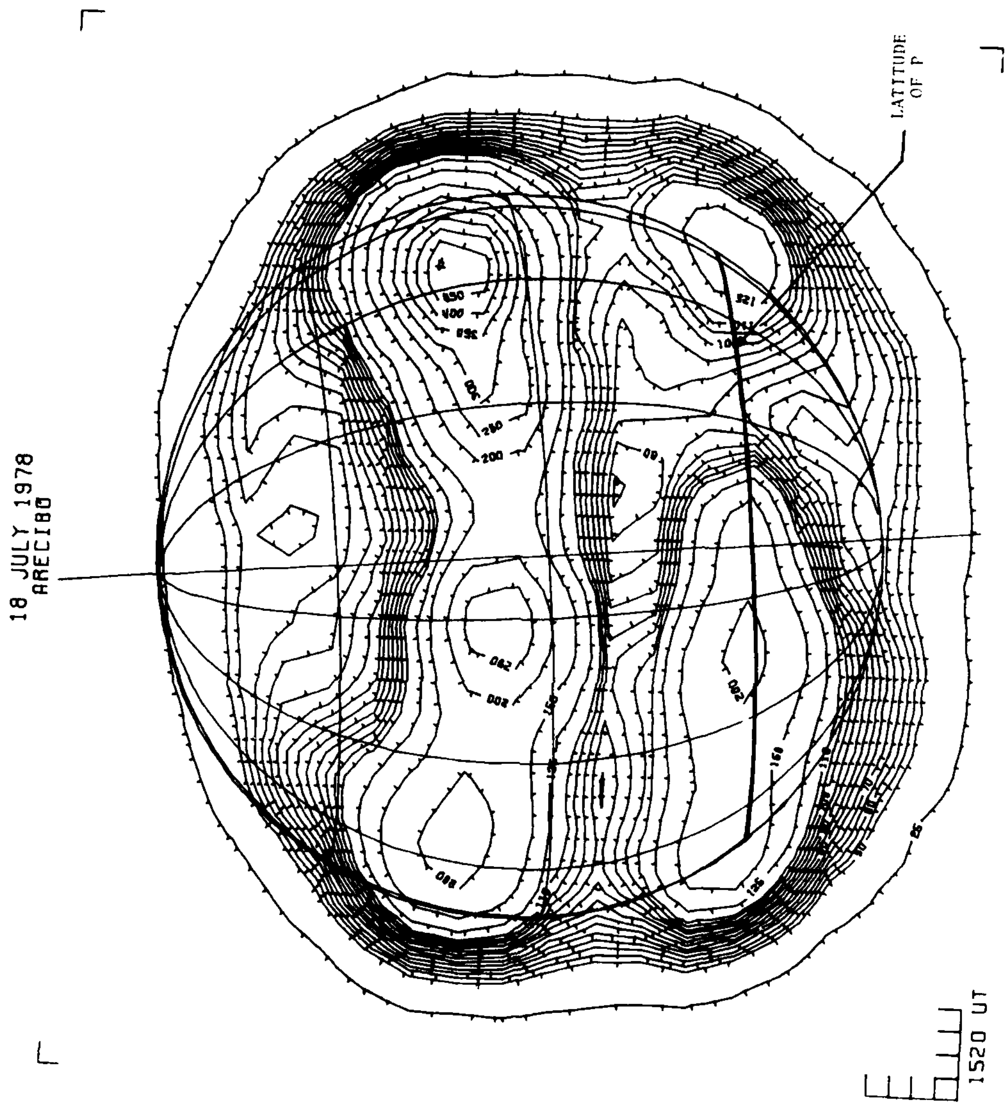

FIGURE 18

spectroheliograms as is shown in the synoptic map (see Figure 13).

The shape and position of the hole as observed at radio frequencies is somewhat different from the shape and position shown in the 10830 Å synoptic map. At radio frequencies the hole appears somewhat broader and also appears to be ahead of its synoptic map position. This may indicate that the scintillation effects should have occurred a day earlier than would be estimated from the synoptic map. The radio maps also show more internal structure of the coronal hole, which does not show up on the synoptic map. In fact, the path of the scintillation point, P, took it through a region of the coronal hole which shows significantly less brightness contrast in the radio maps than other parts of the coronal hole.

The longitude difference of the scintillation point [source 3C161] was +37 degrees and the solar wind speed was low (about 400 km/sec). The net delay, T, should therefore have been approximately +5 days and we would therefore expect a high speed solar wind stream to start around July 23. If, as indicated by the radio data, the coronal hole crossed the meridian about a day earlier than indicated by the 10830 Å synoptic map, then the high speed solar wind should have occurred on about July 22. As can be seen in Figure 13, however, the solar wind speed remained around or below 400 km/sec for an extended period of time around these dates. There is, in fact, no indication of a high speed solar wind in the entire period from June 28 to August 20 (although some scintillation data are missing).

This is a particularly clear case of a "Poor" correlation. The data in this case strongly suggest that the coronal hole was not producing a high speed solar wind stream at the latitude of the scintillation point, since no reasonable adjustment of the coronal hole boundaries will bring us into a period of high speed solar wind. Since the radio map shows less brightness contrast at this latitude than in the rest of the coronal hole, this may indicate that the radio maps are a more reliable way of identifying the structure of coronal holes than 10830 Å spectroheliograms.

CASE 5, Sept. 25 - Sept. 29, 1978, (Figure 14)

The IPS data for this period are impressive and unambiguous. Following an extended period of low solar wind speeds (less than 400 km/sec) the speed of the solar wind rose suddenly to a peak of nearly 700 km/sec on Sept. 24, 1978 and remained consistently high until Sept. 29. The solar wind speed then declined rapidly to a value under 500 km/sec and then further to values below 400 km/sec where it remained for several more days. In this case the scintillation point was never within the area of a coronal hole during this period, but rather in the region between two large coronal holes. This may again be a case in which the coronal hole structures were not in fact accurately reflected in the 10830 Å synoptic maps. It seems likely that the high speed solar wind observed may have been due to either of these two areas, which may in fact have coalesced into one hole in the corona. The chromospheric structure, however, shows an intense active region (McMath 15551) situated between the two coronal holes, and it is also possible that the high speed solar wind was produced by the active region rather than by a coronal hole.

Because the presence of the active region complicates the analysis of this case, and since the scintillation point is not actually within the coronal hole area we consider this case to be only a "Fair" correlation.

<u>CASE 6, May 19 - July 21, 1979, (Figure 17)</u>

This is a good example of a large, stable coronal hole that lasted for several Carrington rotations. It passed by the scintillation point [source 3C161] three times, and each time high speed solar wind streams were observed. In the first passage the point P fell slightly outside the apparent area of the coronal hole on two separate occasions, but the solar wind speed showed no significant changes and remained generally high. This may again reflect an uncertainty in the actual boundary of the coronal hole as obtained from the 10830 Å synoptic maps. Alternatively, this may reflect a situation in which the solar wind streams spread out and diverged from straight line radial propagation, thus broadening the effective area of the coronal hole.

In the second passage there was a period of low solar wind speeds when high speeds would have been expected. The solar wind speed started to increase toward a maximum before the expected time and decreased toward low speeds also before the expected time. As can be seen in Fig. 17, this coronal hole also had a large equatorial extension which preceeded the main area of the hole. If the high speed solar wind emanated primarily from that equatorial portion of the hole, this would explain the apparent early increase and decrease of the solar wind speed observed in the IPS data.

In the third passage the equatorial part of the hole had been separated from the main area of the hole, an indication that the hole was breaking up and disappearing. The IPS data were more variable than on the two previous passages and the apparent peak appeared again to have occured before the expected time, although missing IPS data do not allow an unambiguous determination of the time of the peak.

Although missing data complicates the analysis of this case, the fact that this coronal hole lasted for three rotations and high speed wind streams were observed during each passage makes the correlation of the IPS data with the coronal hole very firm. We therefore consider this to be a "Very Good" correlation.

8. RESULTS AND CONCLUSIONS

As seen from Table 2 and the histogram in Figure 19, during the two and a half year period (January 1, 1977 to June 30, 1979) of this study, we were able to analyse 26 cases in which high latitude coronal hole data from 10830 Å observations and solar wind velocity data high above or

HISTOGRAM OF THE CORRELATIONS

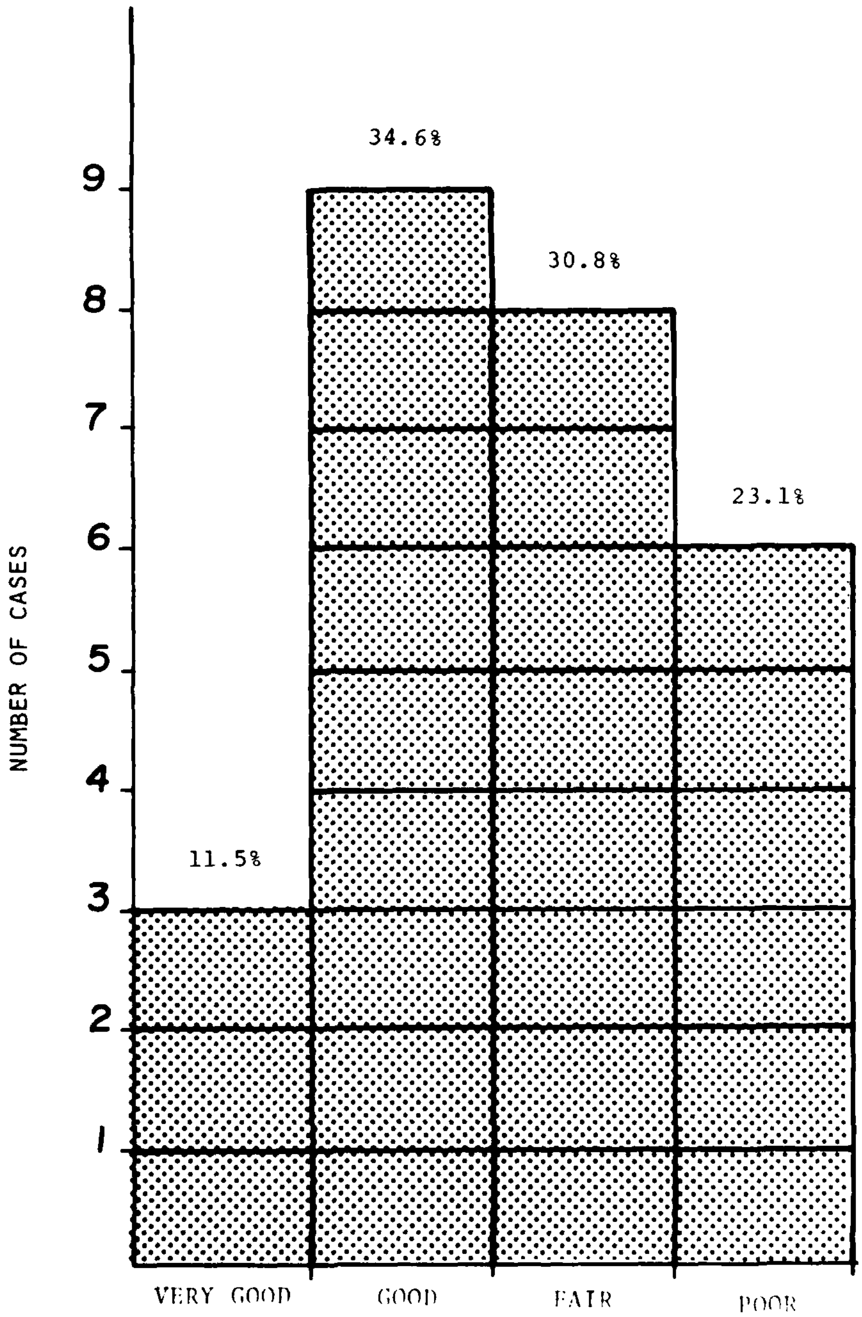

FIGURE 19

below the ecliptic from IPS measurements were simultaneously available. This period, by the way, was ideal for this type of study because, due to the approaching solar maximum, there were no large equatorial coronal holes present to confuse the picture.

Each of the 26 cases was classified in one of four catagories (Very Good, Good, Fair, and Poor) according to the criteria specified in Section 5. The results are given in Table 3.

TABLE 3

Correlation	No. of Cases	Percentage
Very Good	3	11.5
Good	9	34.6
Fair	8	30.8
Poor	6	23.1
Total	26	100.0

This analysis indicates that in about 50% of the cases ("Very Good", and "Good") there was a significant increase (>25%) above the average in the solar wind speed during the period that the scintillation point was aligned with the area of the coronal hole, and that there was also a substantial correspondence between coronal hole features and changes in the solar wind speed.

If one were also to include the cases classified as "Fair", then in more than 75% of the cases there was a general increase in the solar wind speed during a more tolerantly defined correspondence period. The greater tolerance in the correspondence period is not unreasonable given the uncertainties in determining the coronal hole boundaries from the 10830 Å data and the uncertainties in determining the true solar wind speed from the IPS data.

The above results point strongly toward a positive correlation between high latitude coronal holes and high speed solar wind streams high above or below the ecliptic. There are, however, also the "Poor" cases (roughly 25% of the total) and of course the lack in most cases of a close correspondence of solar wind changes with specific coronal hole features. One could adopt the attitude that the correlation is always poor and that the good cases are merely fortuitous coincidences. It would seem more reasonable, however, especially in view of the already established good correlation of large equatorial coronal holes with high speed solar wind streams, to accept the cases of good correlation as valid and try to understand the reasons that led to a poor correlation in the other cases. These reasons could include:

1. The simplifying assumptions of radial propagation and constant speeds for the solar wind streams may not always be valid.
2. The solar wind speeds inferred from the IPS measurements may not always be accurate. Comparison of the UCSD and Toyokawa data on a day to day basis indicates that large uncertainties can exist in the solar wind speeds as derived from IPS measurements (note, however, that some instances of apparent disagreement in solar wind speed may be due to the

approximately 12 hour difference between the time UCSD and Toyokawa make their daily observations).

3. The fact that we only have one solar wind speed reading per day, which corresponds to about 13.5 degrees of solar rotation, might be responsible for the lack of detailed correspondence of coronal hole features with changes in the velocity of the solar wind. Such changes in the solar wind speed are undoubtedly dynamic in nature and might vary substantially in the course of a single day. In addition, coronal holes of small longitudinal extent might be missed entirely.
4. Uncertainties about the exact boundaries of coronal holes as determined from the He 10830 A spectroheliograms, which actually observe the chromosphere and not the corona, may lead to misdating the times at which the coronal hole was aligned with the scintillation point.
5. The shape of the coronal hole may have changed to some extent between the time it crossed the central meridian (as determined from the 10830 Å synoptic maps) and the time it was aligned with the scintillation point.
6. The presence of active regions near coronal holes may mask the effects of coronal holes by generating their own solar wind streams and perhaps distorting the wind streams produced by the coronal holes.
7. Some coronal holes might not produce high speed solar wind streams on a continuous basis or the speed of the stream they produce may vary substantially even during

the course of one day.

8. Coronal holes may have internal structure which is not visible in the 10830 Å synoptic maps. Thus, some areas of a coronal hole may produce high speed solar wind streams while other areas do not.

9. The interaction of a relatively weak solar wind stream with the slower solar wind or with other solar wind streams in interplanetary space could attenuate it to the point that it would not appear as a high speed solar wind stream by the time it reached the scintillation point.

10. The interaction of a relatively weak high speed solar wind stream with the interplanetary magnetic field could divert its direction of propagation and hence make it miss the scintillation point estimated on the basis of radial propagation.

It is clear from the above that there are several factors which could easily explain the lack of a positive correlation in many cases. It is also clear that a much better correlation is to be expected, as it has also been observed, in the cases of large coronal holes where several days of IPS data reinforce the confidence in the presence of a broad and intense solar wind stream. Smaller coronal holes, on the other hand, are bound to produce weaker and narrower streams which are more difficult to detect, especially when the scintillation point crosses only marginally through the area of the coronal hole.

In conclusion, given the uncertainties in both the IPS and the He 10830 Å data and the propagation problems weak solar wind streams might encounter in interplanetary space, we feel that the documentation of several cases of good correlation strengthens the point that high latitude coronal holes tend to produce high speed solar wind streams just as do the large equatorial ones. As expected, however, the solar wind effects observed are proportional to the sizes of the coronal holes and could be easily missed for the smaller ones (or the fringes of larger coronal holes) with the means of detection (interplanetary scintillation) presently available.

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